OBSERVATIONAL BLACK HOLE SPECTROSCOPY: RINGDOWN TESTS OF GENERAL RELATIVITY

Gregorio Carullo

QFC 2019

Università di Pisa

OUTLINE OF THE PRESENTATION

- Introduction

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- **Quasi-normal modes** of a black hole

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- **Population inference** of deviation from General Relativity
- Conclusions

BINARY BLACK HOLES COALESCENCES

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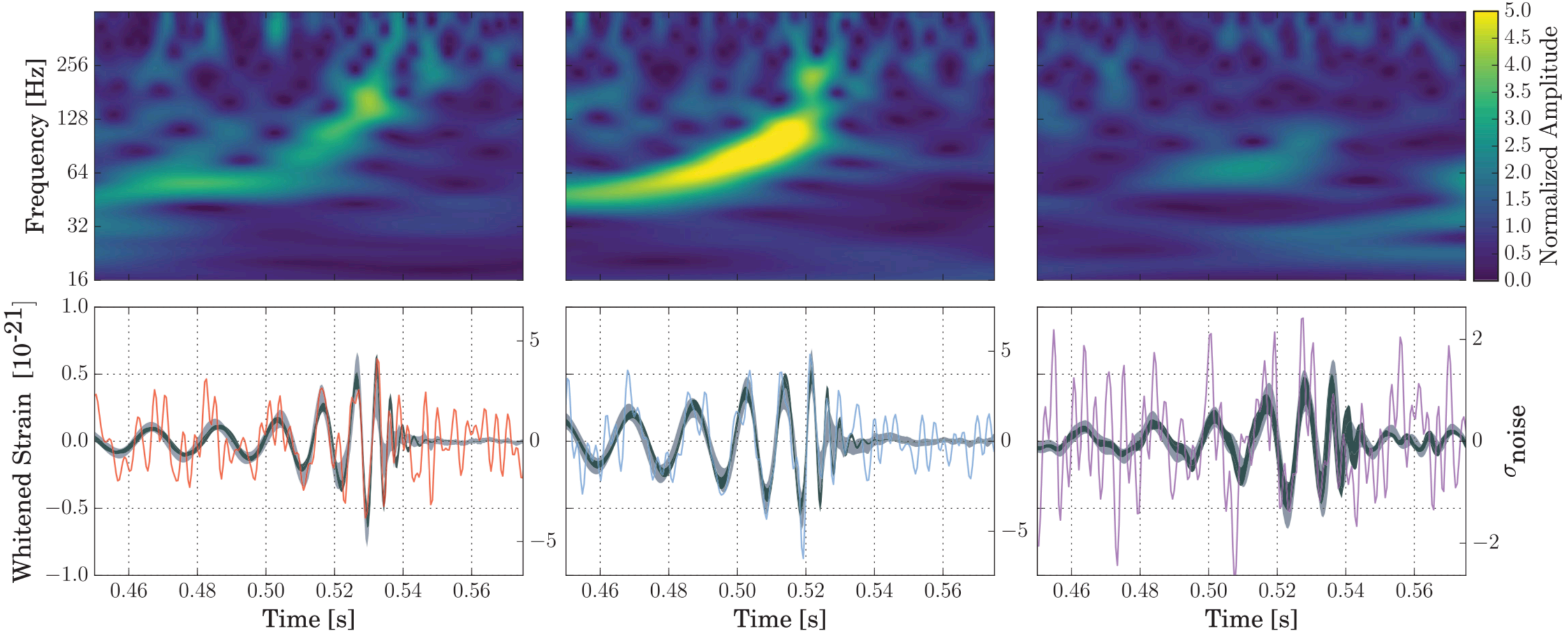
- Coalescences of binary black holes emit **gravitational waves** detectable on earth



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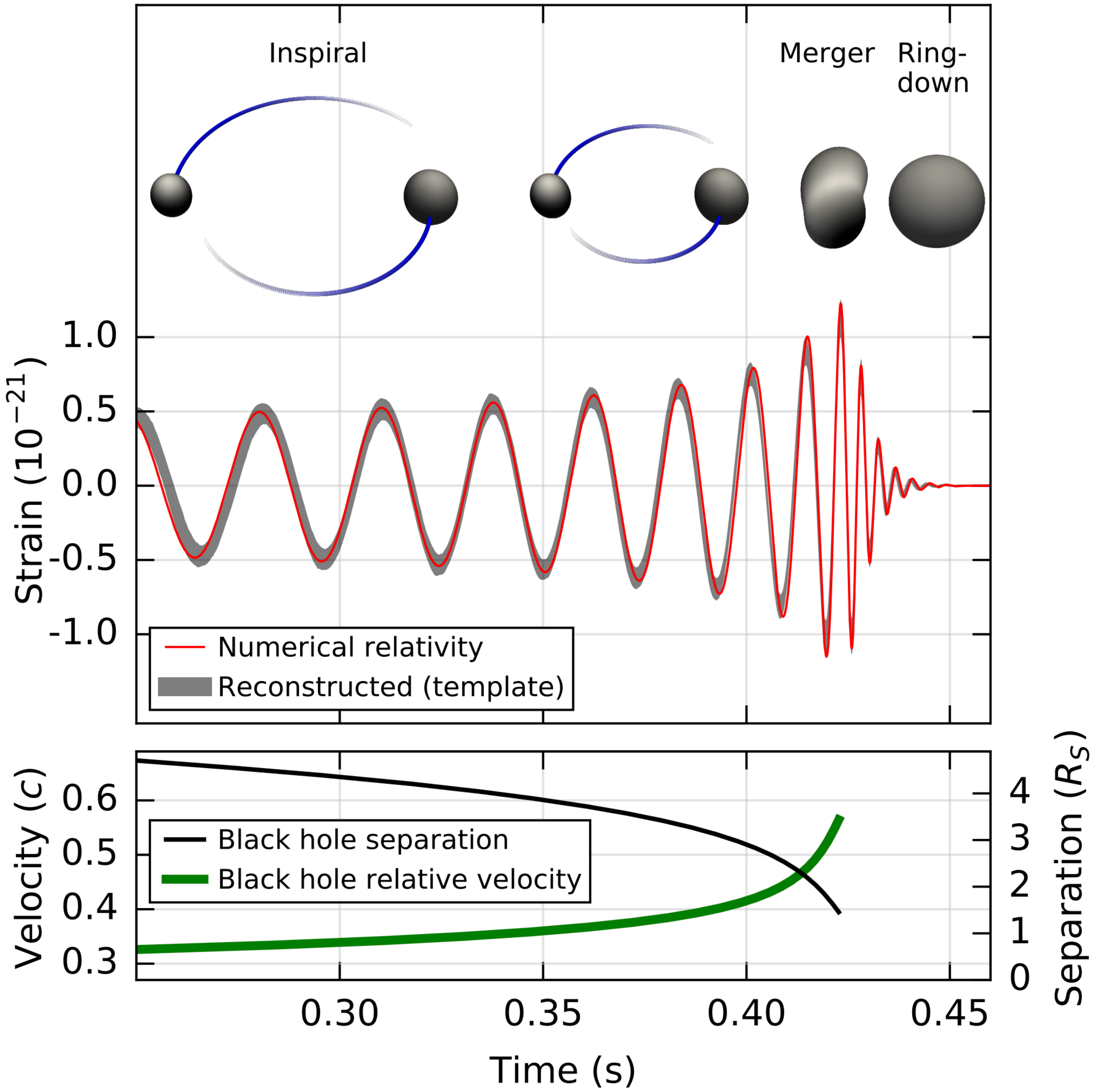
GW170814 discovery paper, LVC collaboration, PRL 119, 141101 (2017)

BINARY BLACK HOLES COALESCENCES

- Three main phases of the coalescence:



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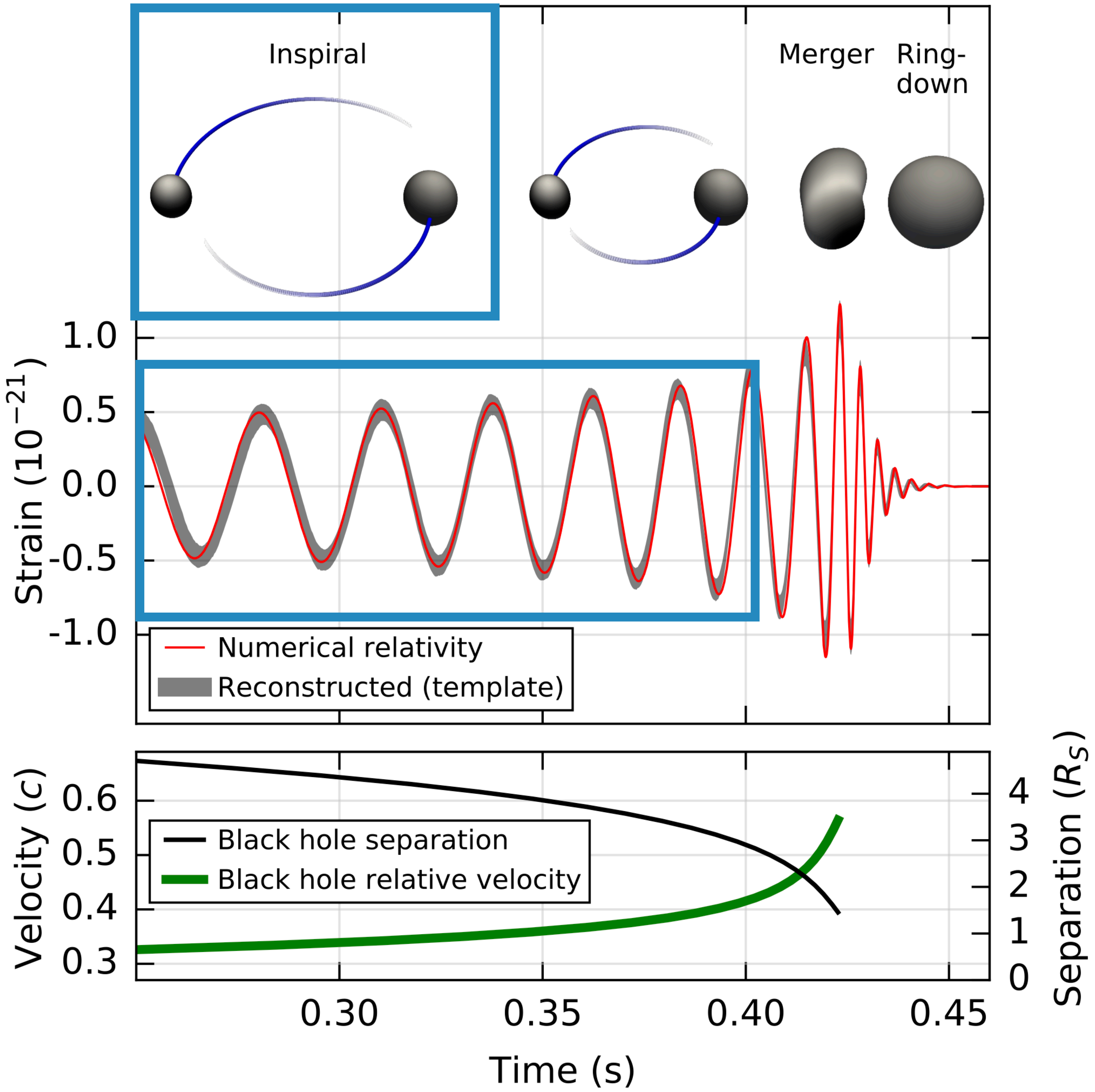
  - **Inspiral**: Post-Newtonian theory



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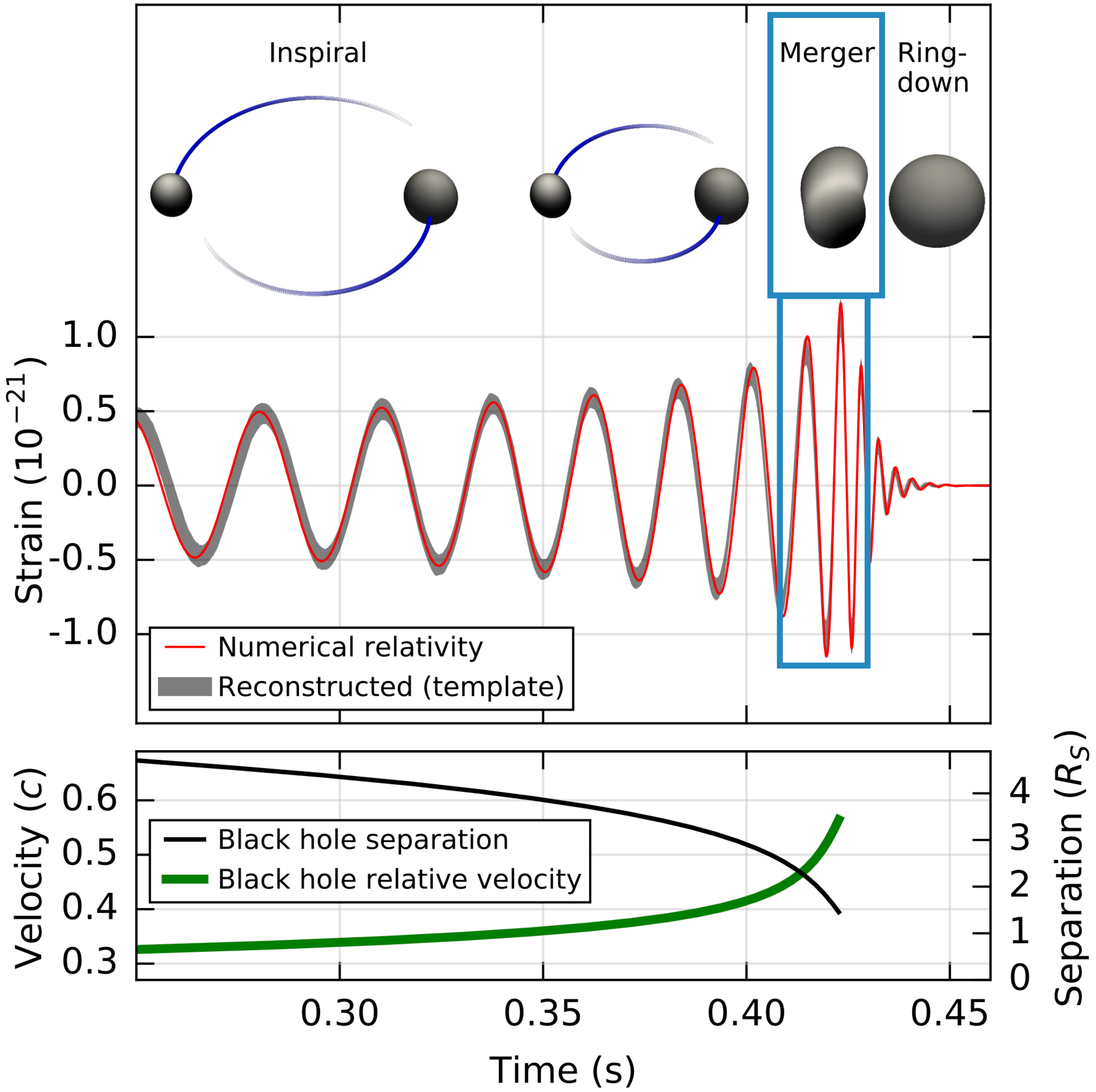
  - **Plunge-merger**: numerical simulations



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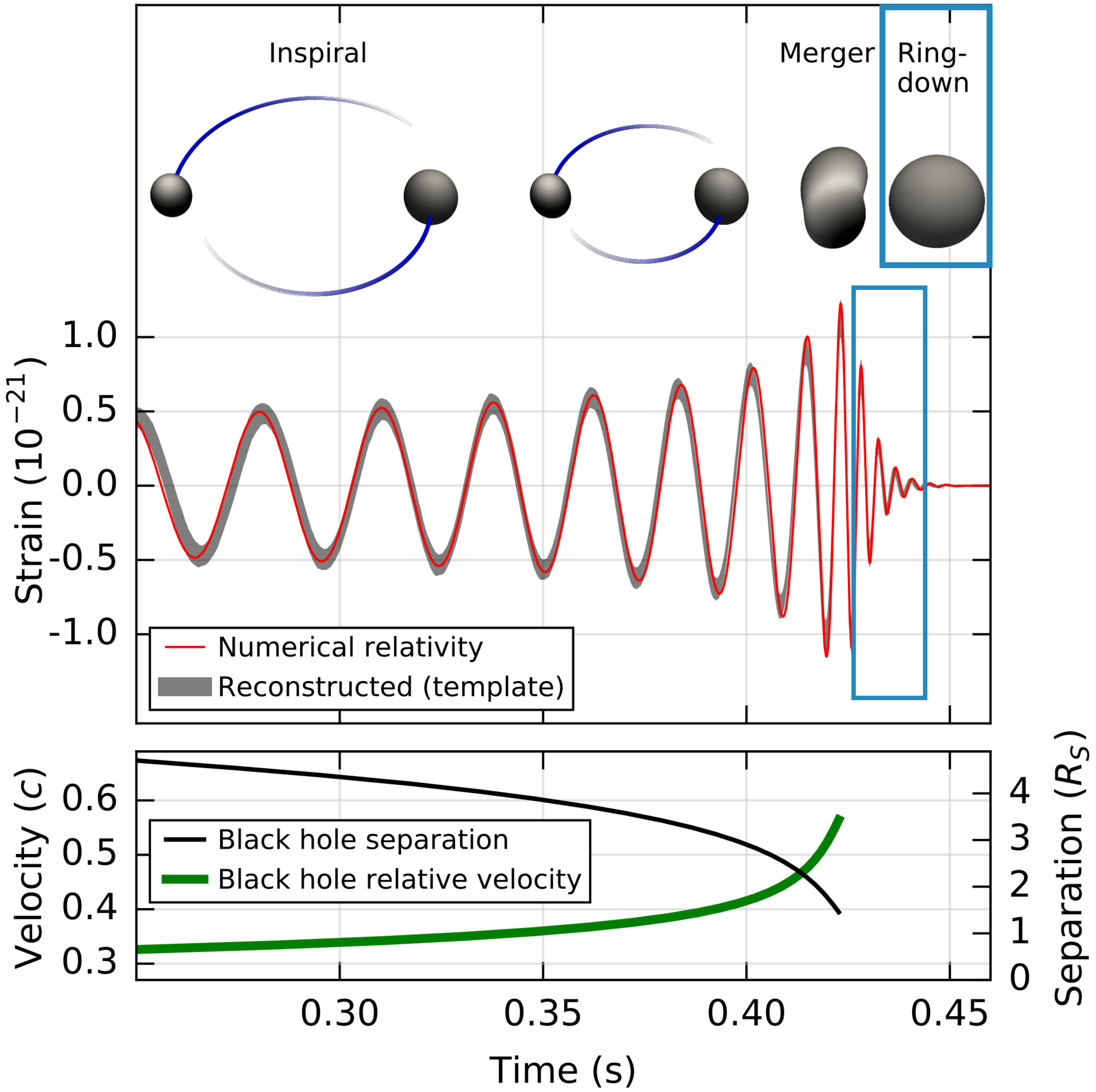
  - **Plunge-merger**: numerical simulations
  - **Ringdown**: perturbation theory and numerical simulations



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- **Space-time** itself can undergo **oscillations** even when no matter is present

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Vishveshwara, Nature 227, 936 (1970)

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- **Space-time** itself can undergo **oscillations** even when no matter is present
- The **ringdown** phase corresponds to the emission of the **normal modes** of the remnant **black hole**, damped by the presence of an **horizon**
- Analytical solution of the **linearized** Einstein equations on a **black hole background**

Regge, Wheeler, Phys. Rev. 108, 1063 (1957)
Zerilli, Phys. Rev. Lett. 24, 737 (1970)
Teukolsky, Astrophysical Journal, vol. 185 (1973)

THE REGGE-WHEELER-ZERILLI EQUATION

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- Linear **perturbations** of the Schwarzschild background:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

$$Z^A := \frac{1}{r}(1 - \frac{2M}{r})h_1$$

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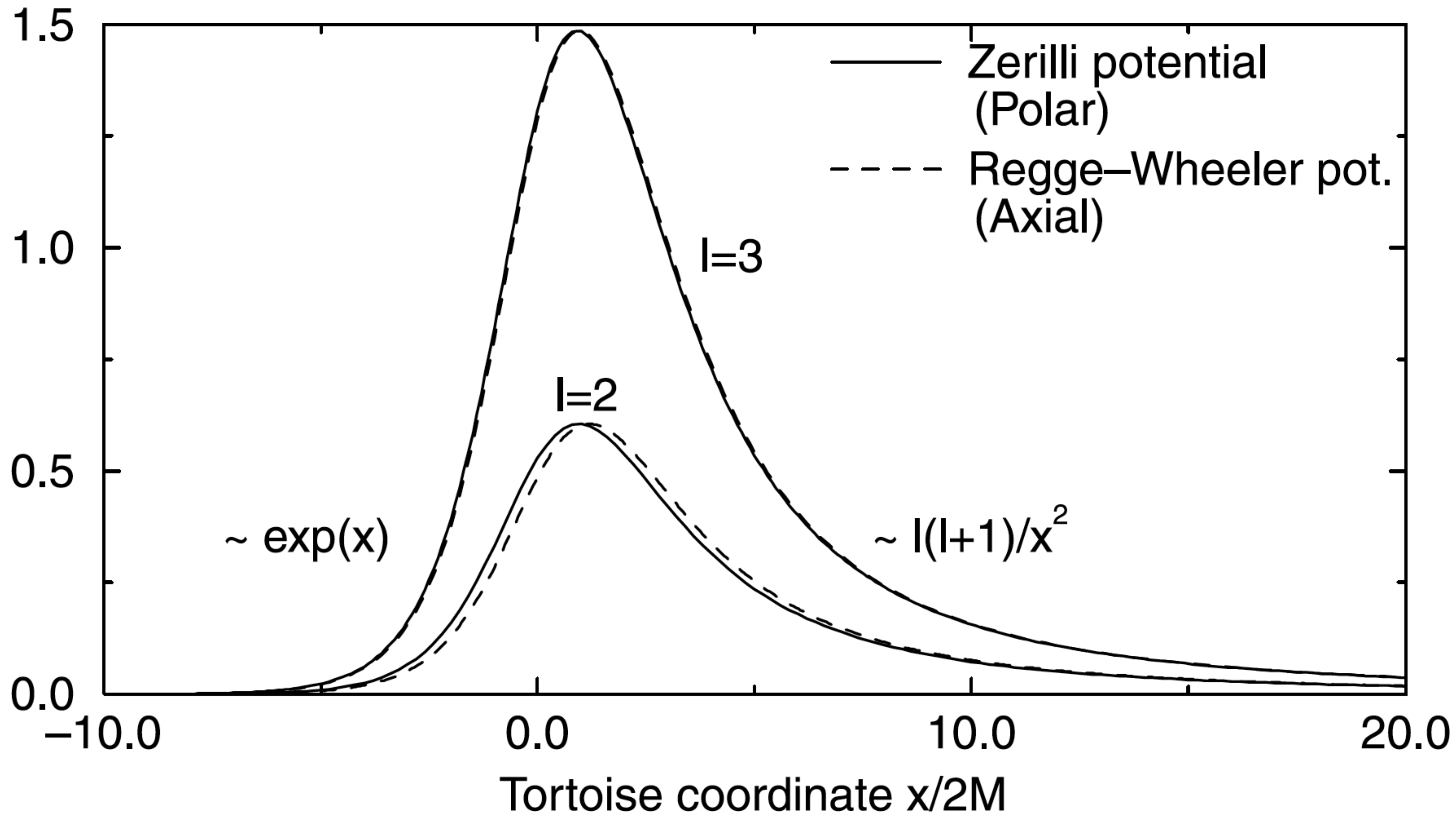
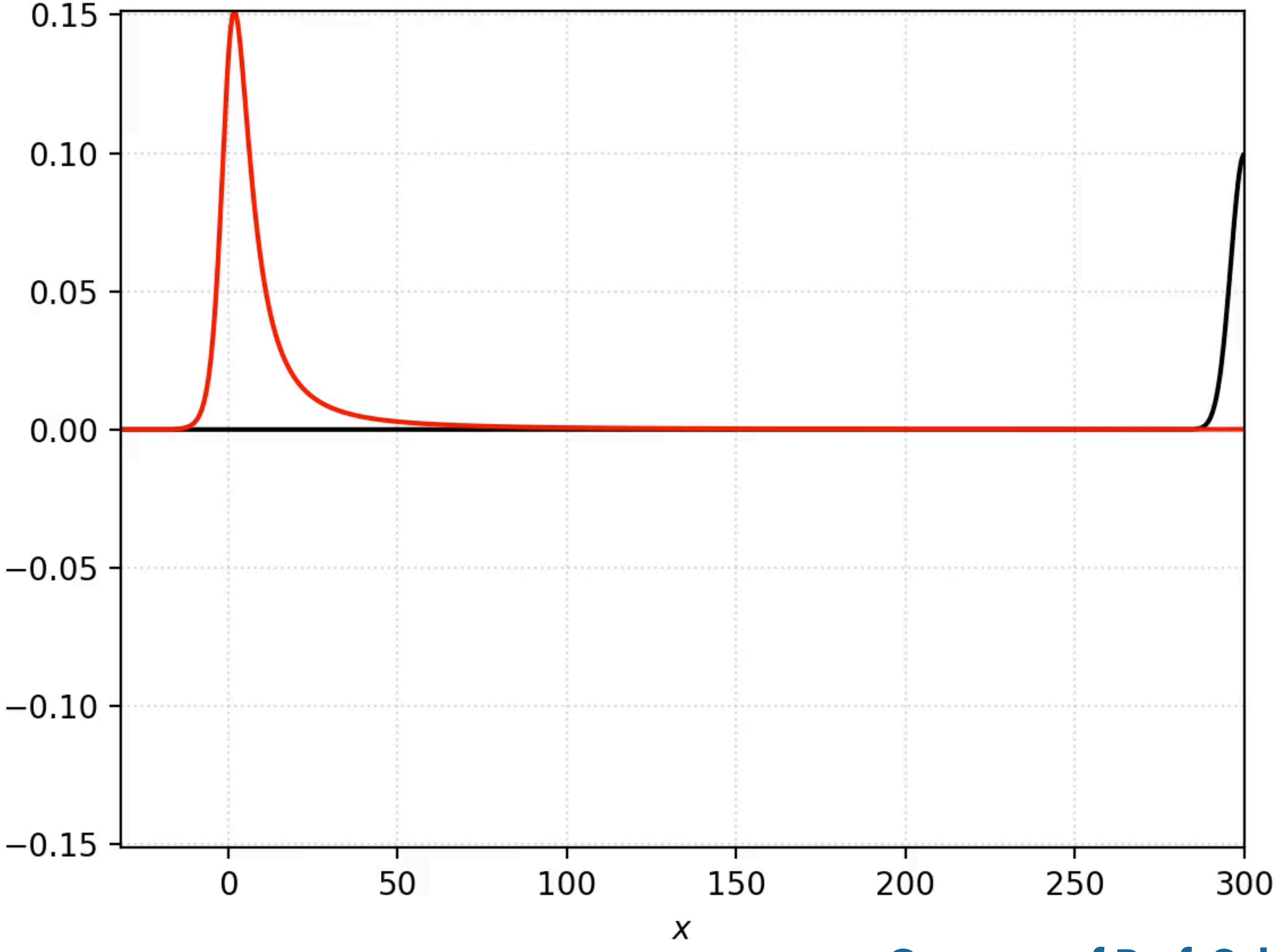
- Einstein's eq.s for the perturbations:

$$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} + V_A(x)\right) Z^A(x,t) = 0$$



Nollert, Characteristic Oscillations of Black Holes and Neutron Stars (CQG, 2000)

The horizon is at -∞



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Courtesy of Prof. Sebastiano Bernuzzi

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

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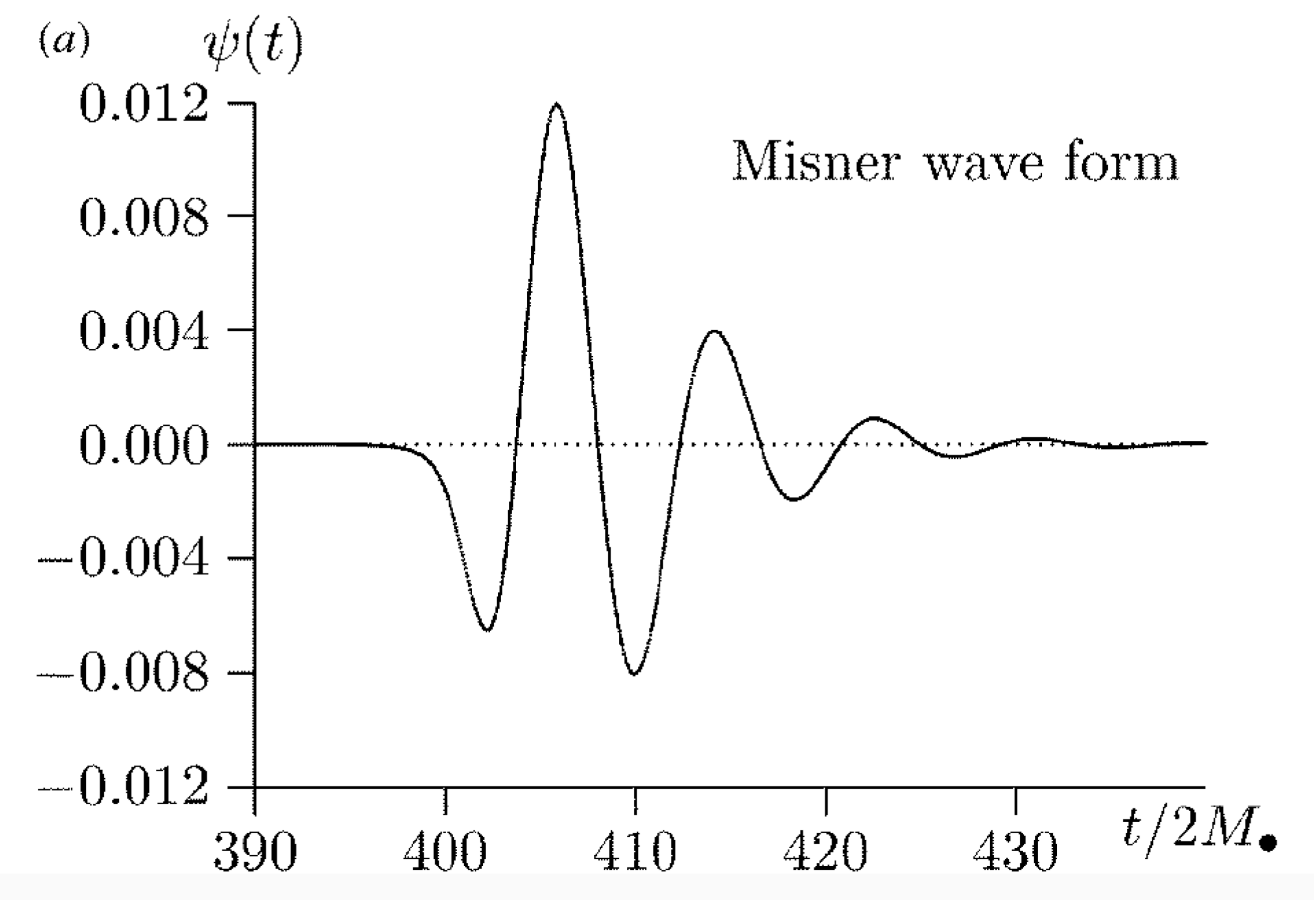
- In terms of gravitational wave multipoles:

$$h_+ - i\,h_\times = -\frac{M}{r}\sum_{l,m,n}\mathcal{A}_{lmn}\,S(\theta,\phi)\,e^{i\omega_{lmn}t}\,e^{-t/\tau_{lmn}}$$



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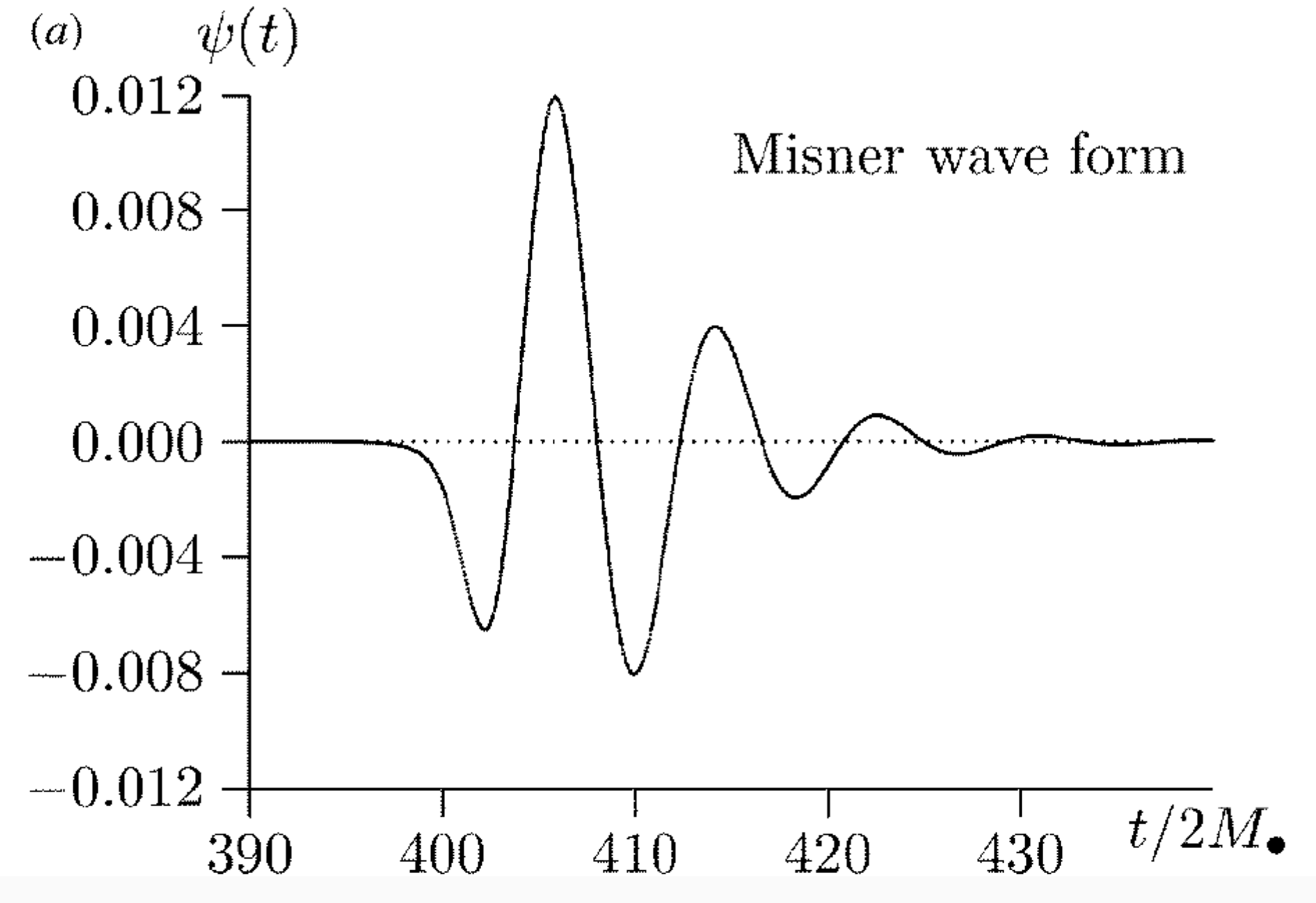

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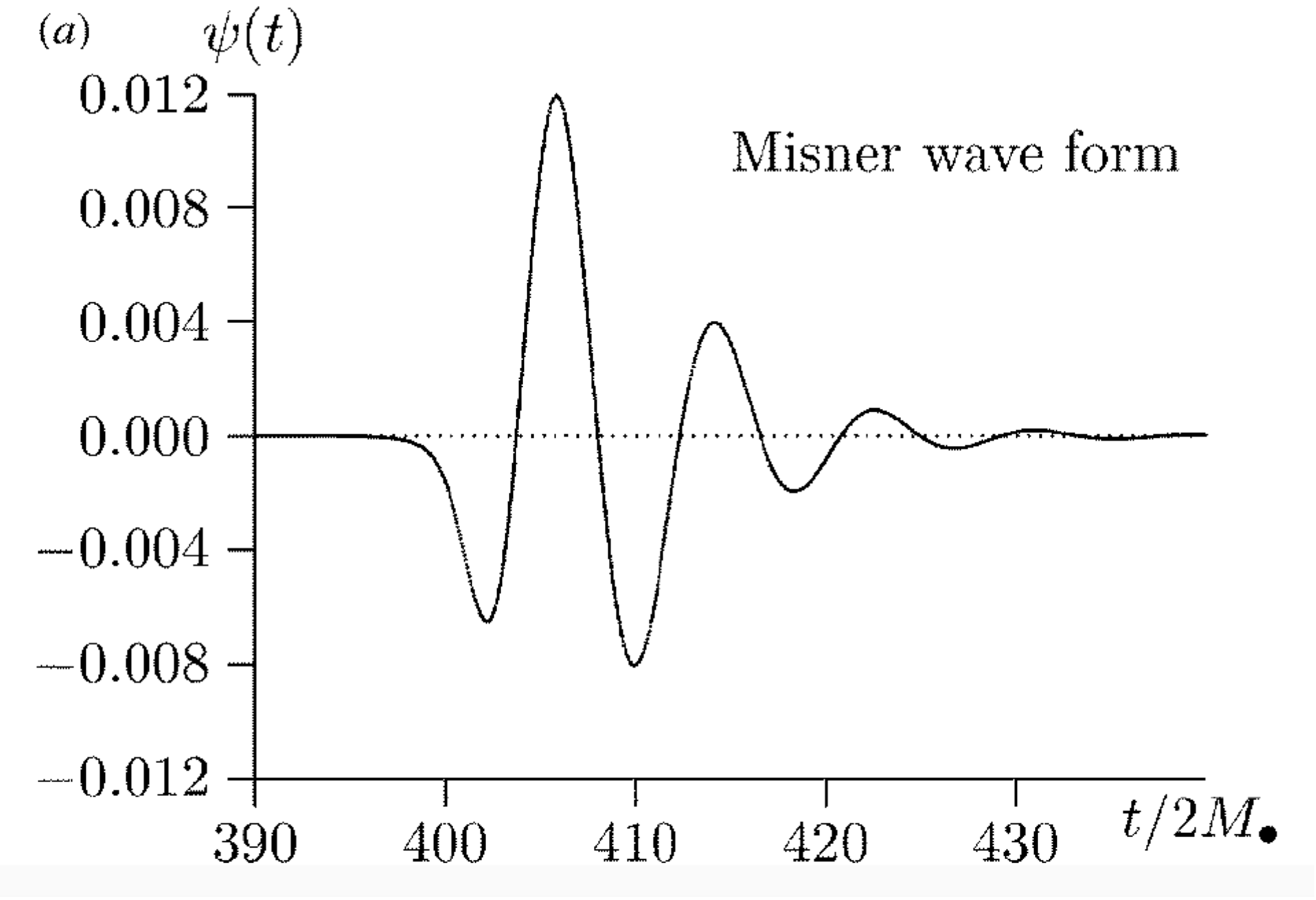

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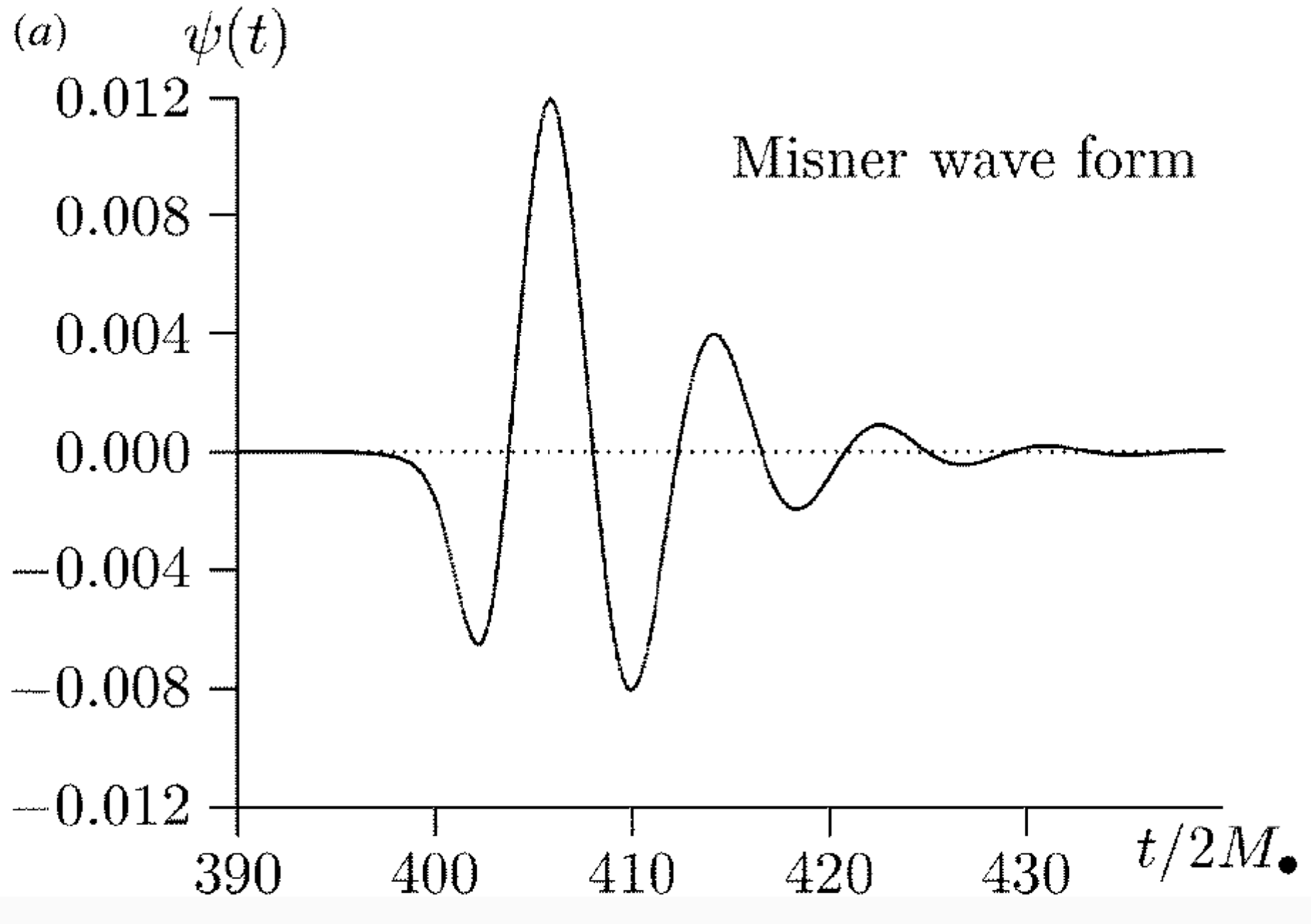
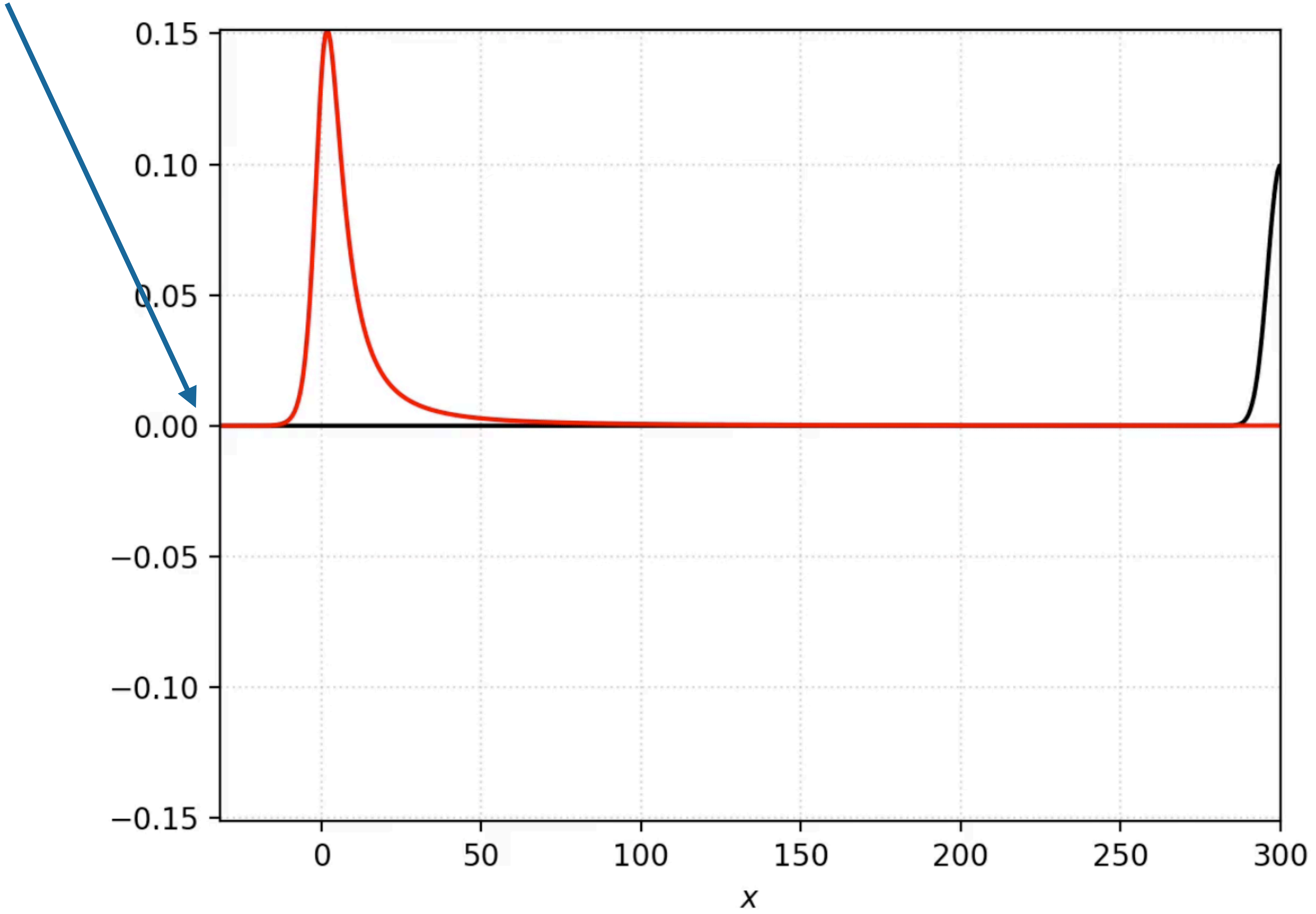


- Frequencies and damping times spectrum predicted by perturbation theory, fixed only by **mass** and **spin** of the black hole
- Amplitudes and relative phases predicted by numerical relativity
- Independent measurement of the **final black hole** parameters, enabling a test of GR predictions

Nollert, Characteristic Oscillations of Black Holes and Neutron Stars (CQG, 2000)

What if there's no complete absorption here?



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Courtesy of Prof. Sebastiano Bernuzzi

ECHOS OF ECOS

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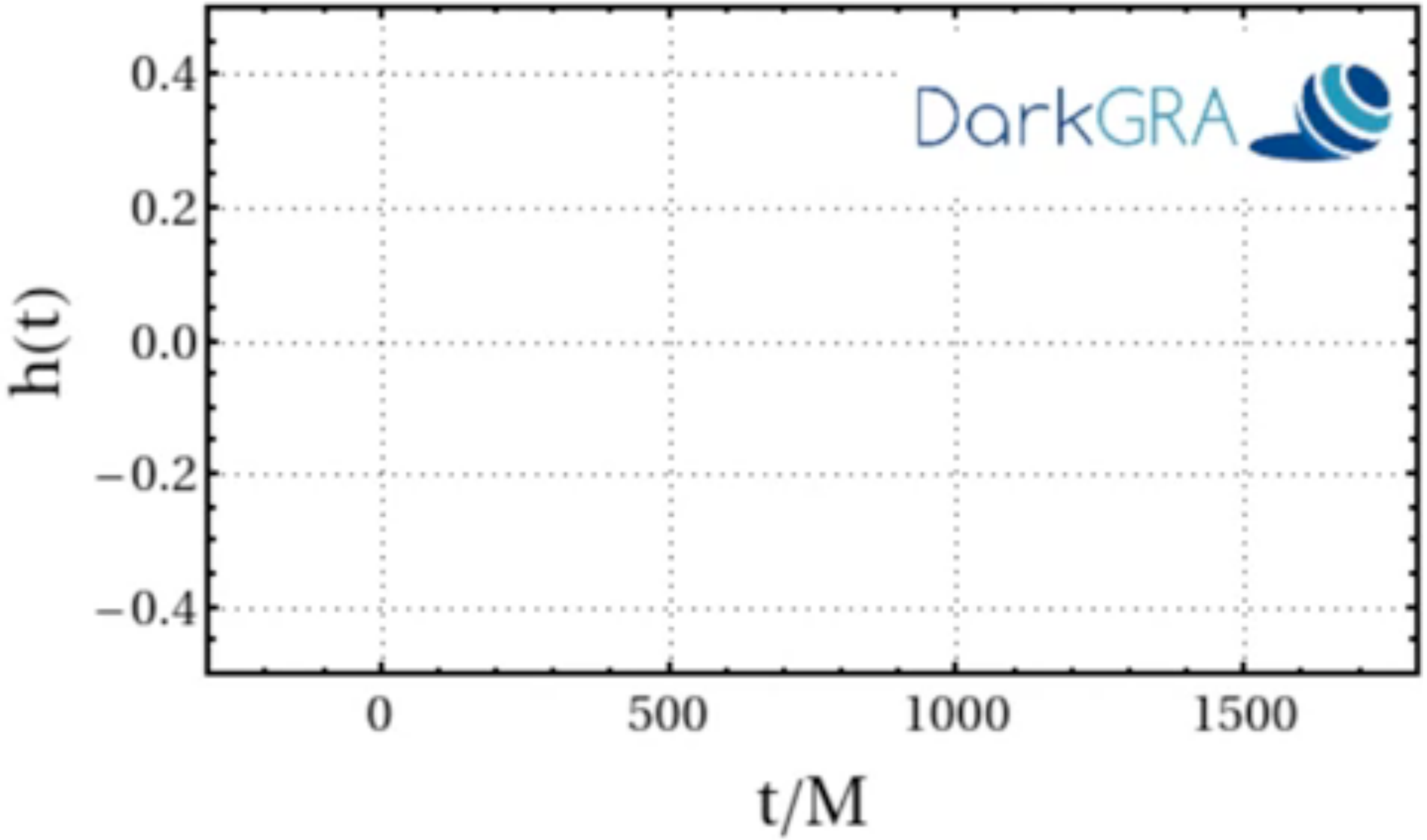
- Extreme compact objects (**ECOs**) are candidates to **mimick** BHs
- Instead of a simple ringdown they produce **echos**
- Echoes are caused by **multiple reflections** between the **potential barrier** and the **would-be-horizon**



GW150914: THE DAY WE SAW A BLACK HOLE RINGING

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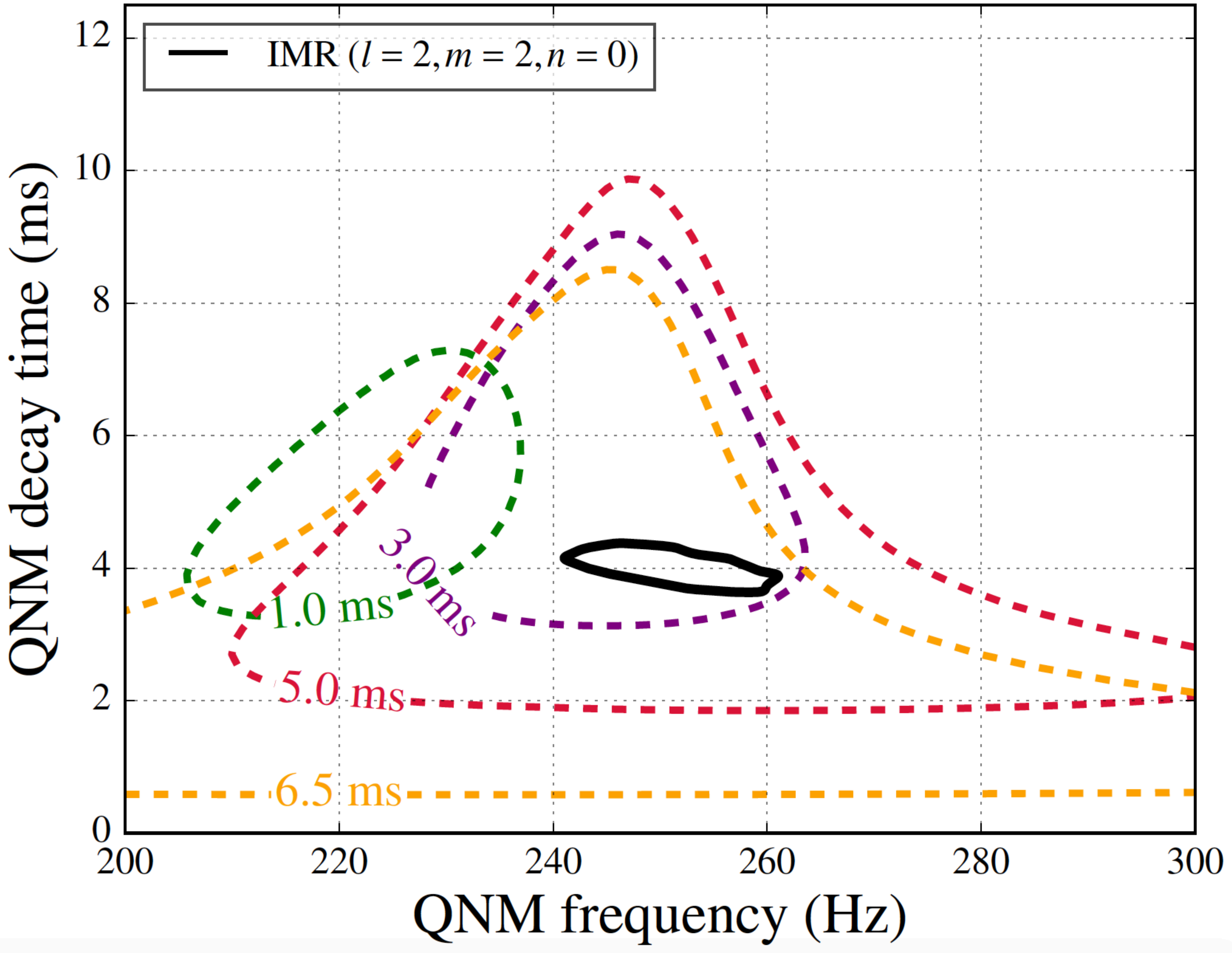
- **First** and ~~only~~ ringdown observation: **GW150914**



Tests of general relativity with GW150914, LVC, Phys. Rev. Lett. 116, 221101 (2016)

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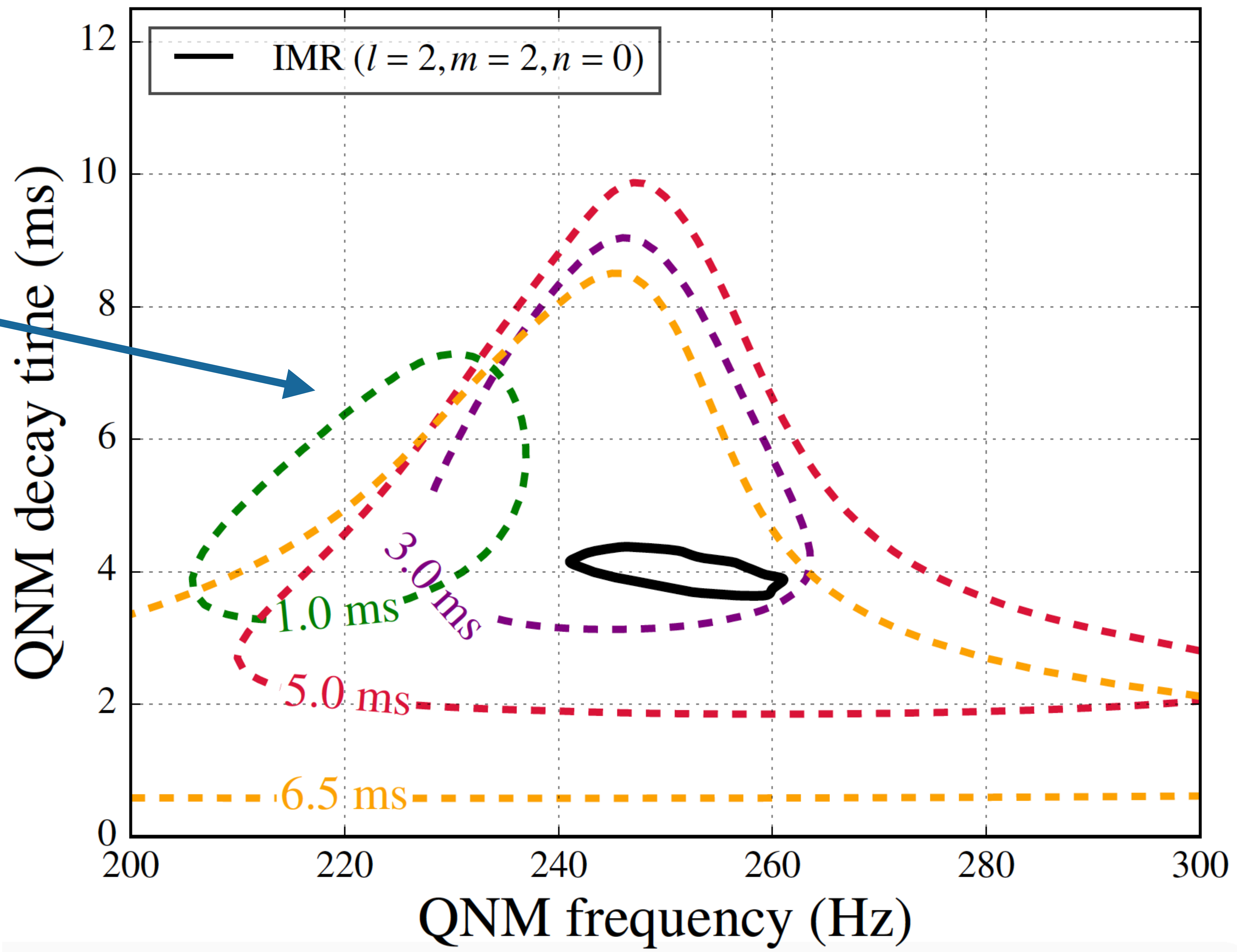

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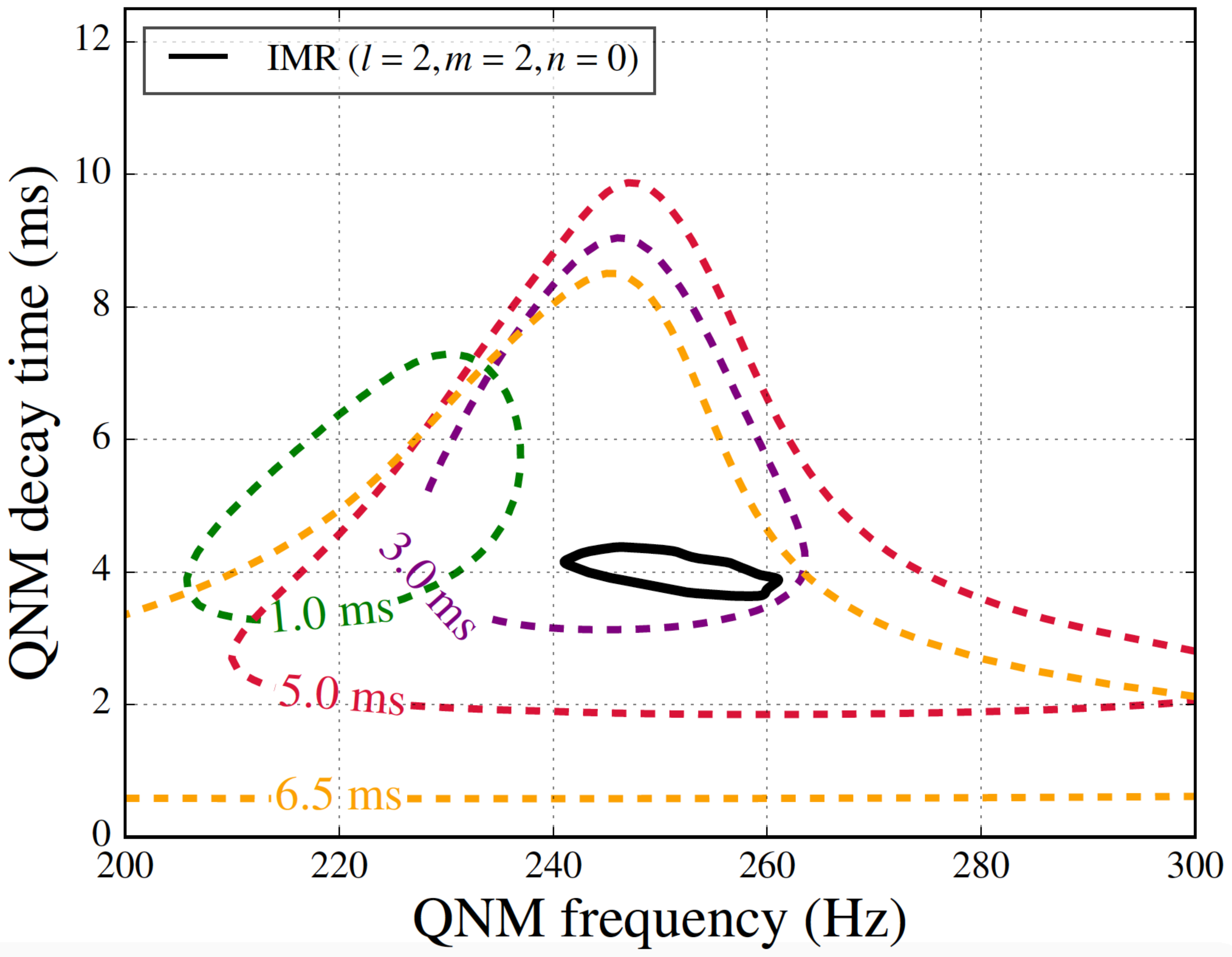

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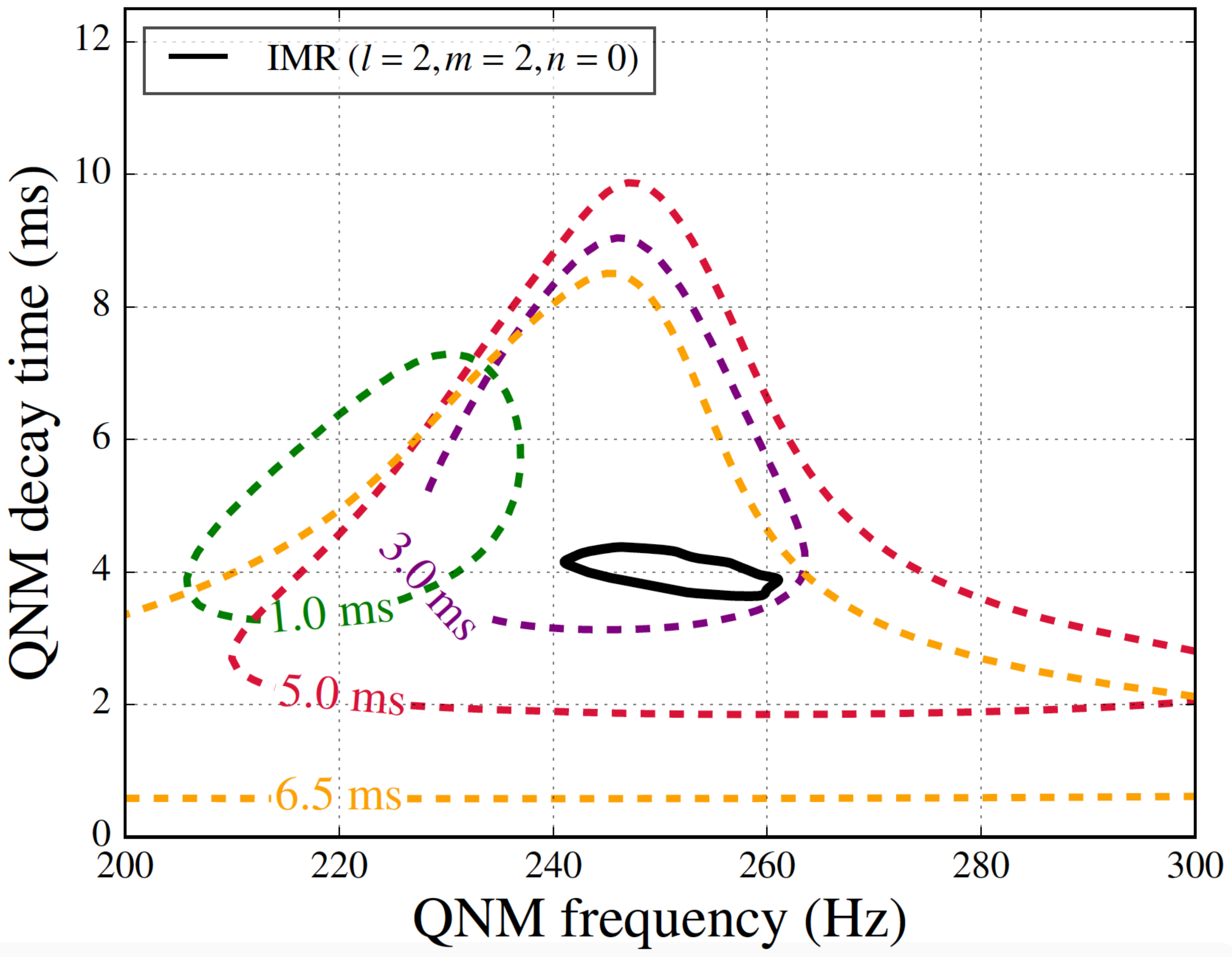

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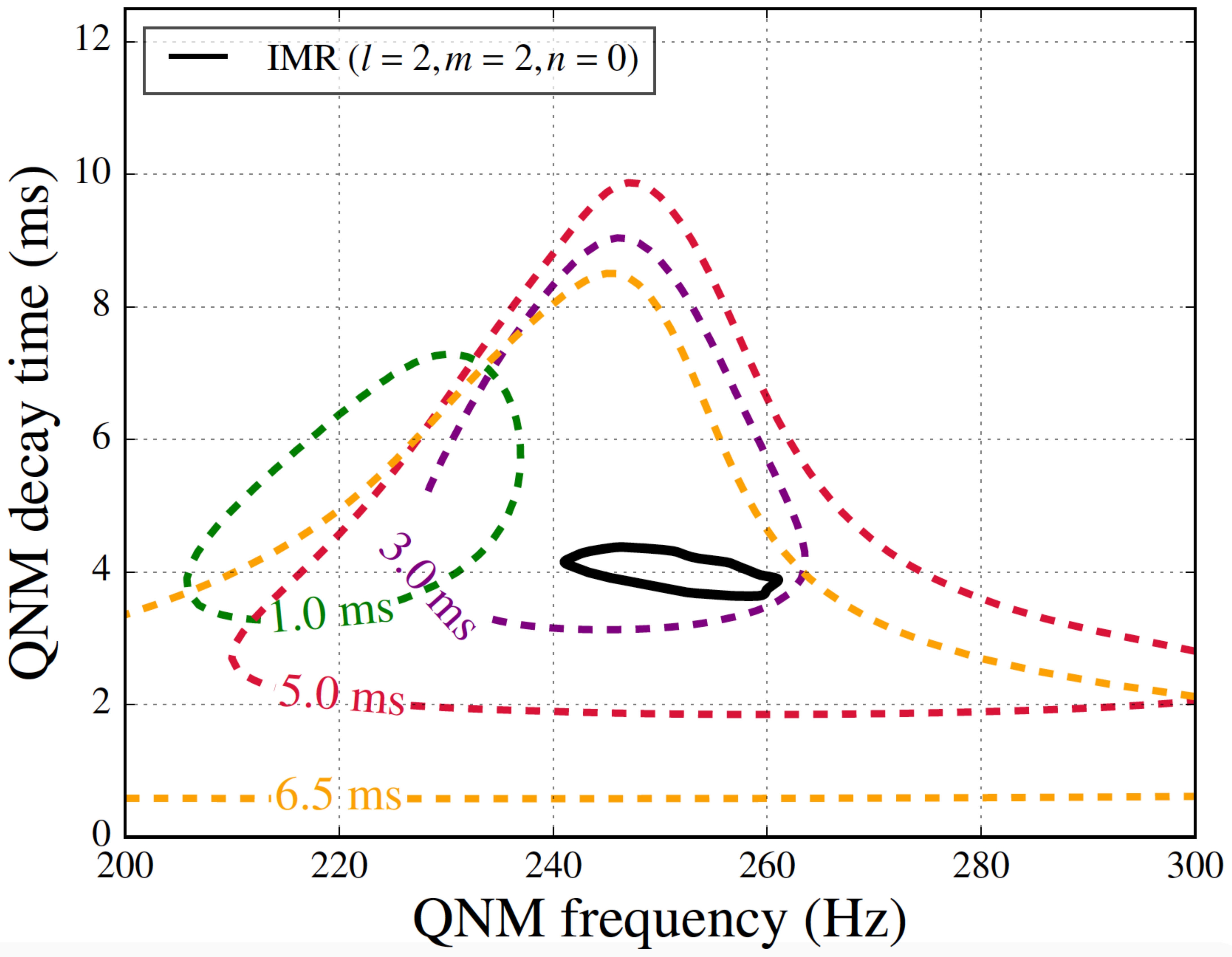
- **Systematics** unclear



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HOW TO PUSH IT FORWARD

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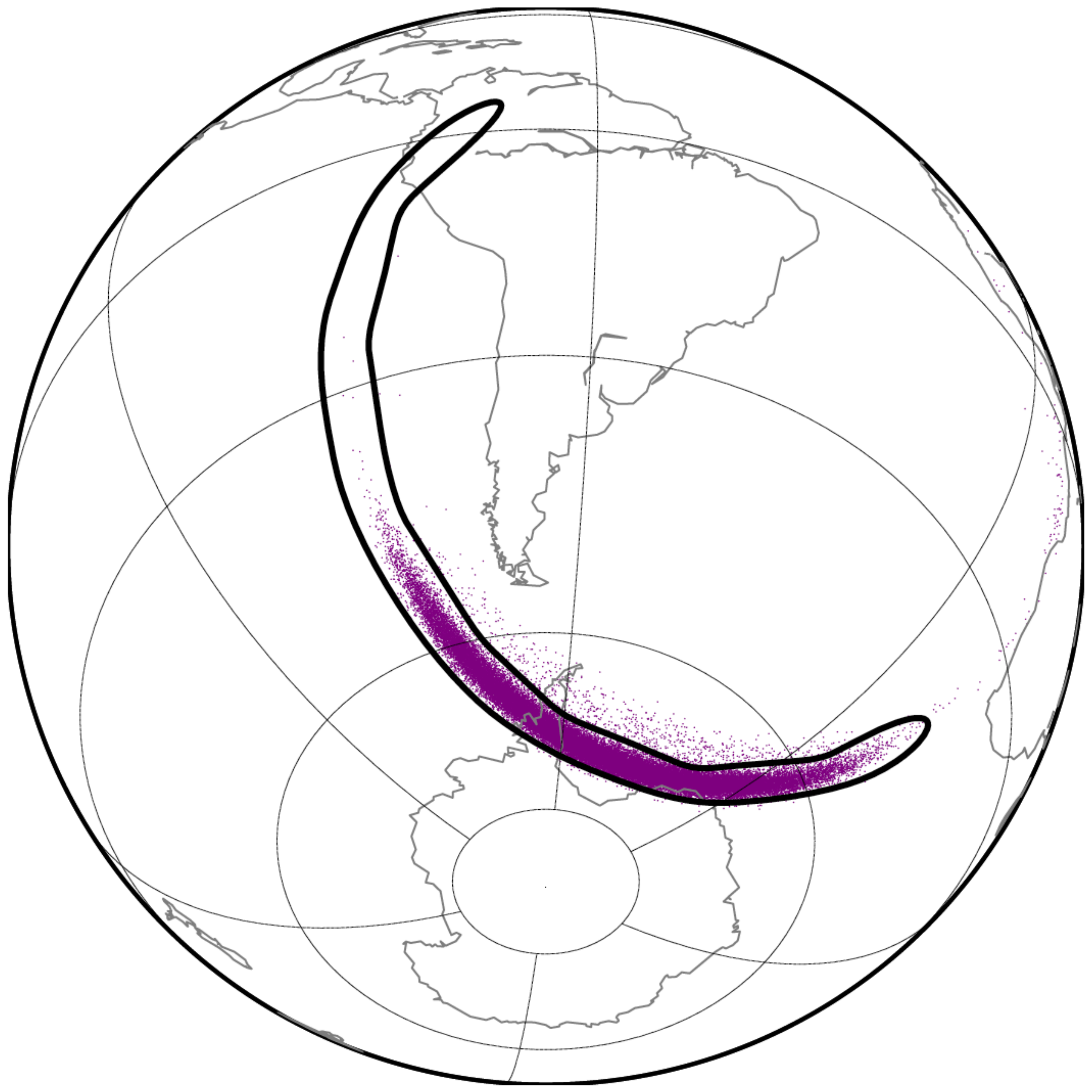
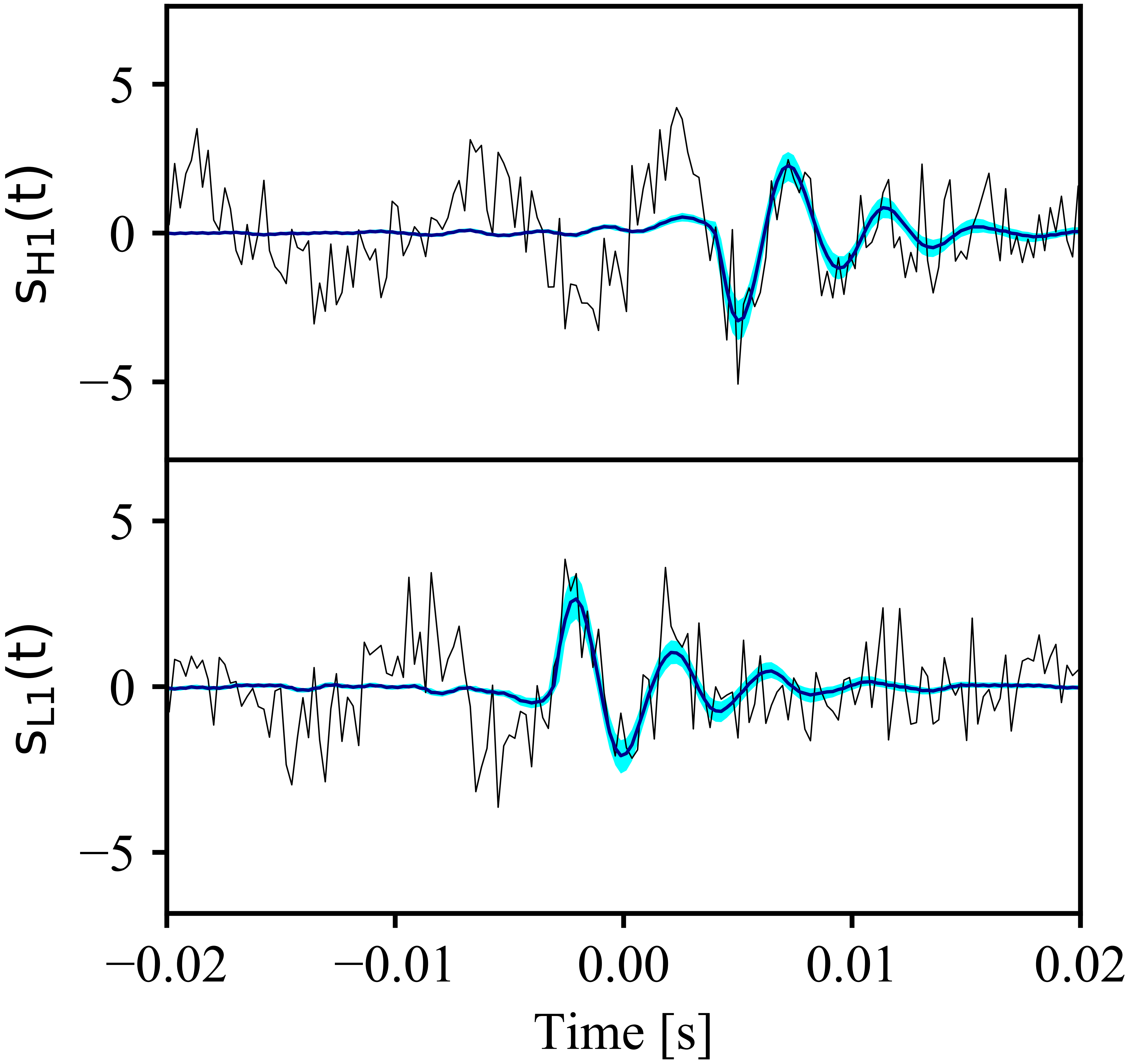
- Unlike standard LVC analysis **time-domain likelihood**
- **Black hole spectroscopy** reformulated as Bayesian model selection
- Identify ringdown in **other signals**
- **Population**-based test of GR?
- Tests of the **no-hair theorem** (read final state conjecture) already with **2G**?

- Reconstructed **whitened waveform** on top of detector data:





Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)

BLACK HOLE SPECTROSCOPY WITH GW150914

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- Introduced in : [1], [2]

[1] Dreyer+, CQG. 21, 787 (2004)
[2] Berti, Cardoso, Will, PRD 73, 064030 (2006)

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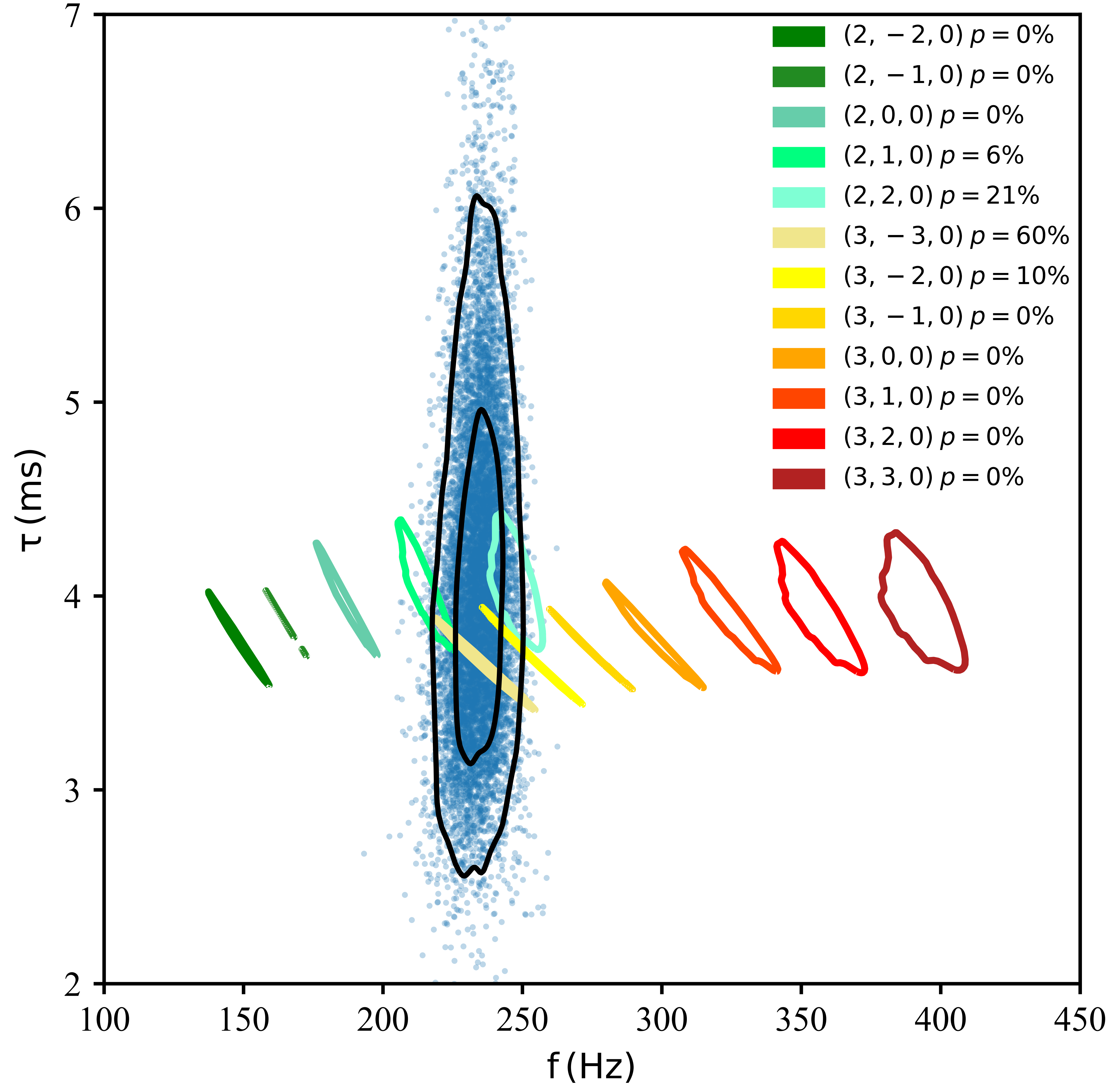
- **Predict** modes frequency: IMR estimates of **progenitors intrinsic parameters** + NR fits [3]



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BLACK HOLE SPECTROSCOPY WITH GW150914

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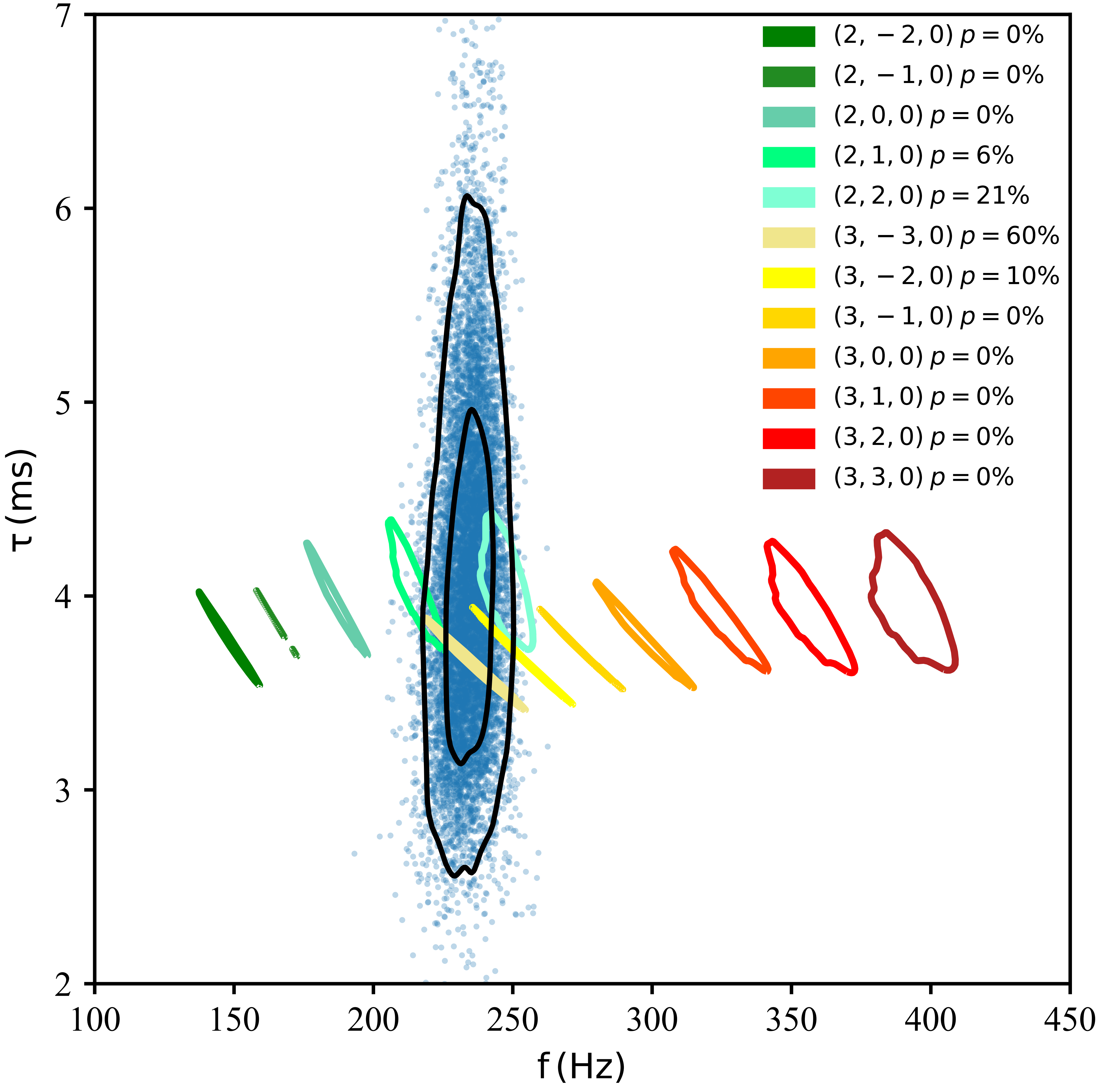
- Introduced in : [1], [2]
- **Predict** modes frequency: IMR estimates of **progenitors intrinsic parameters** + NR fits [3]
- Bayes theorem predicts the **probability** that recovered agnostic posterior corresponds to **given predicted mode**



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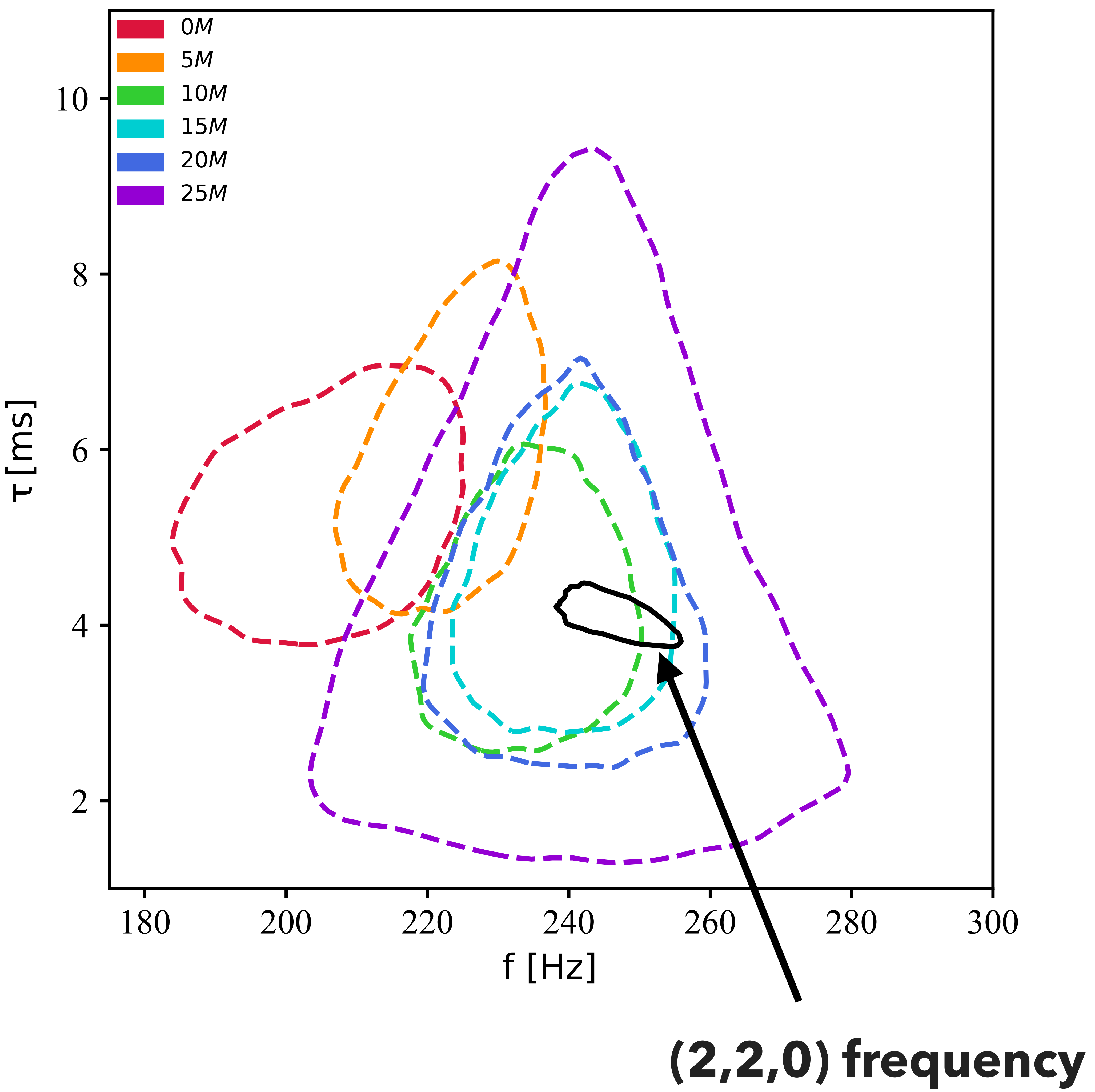
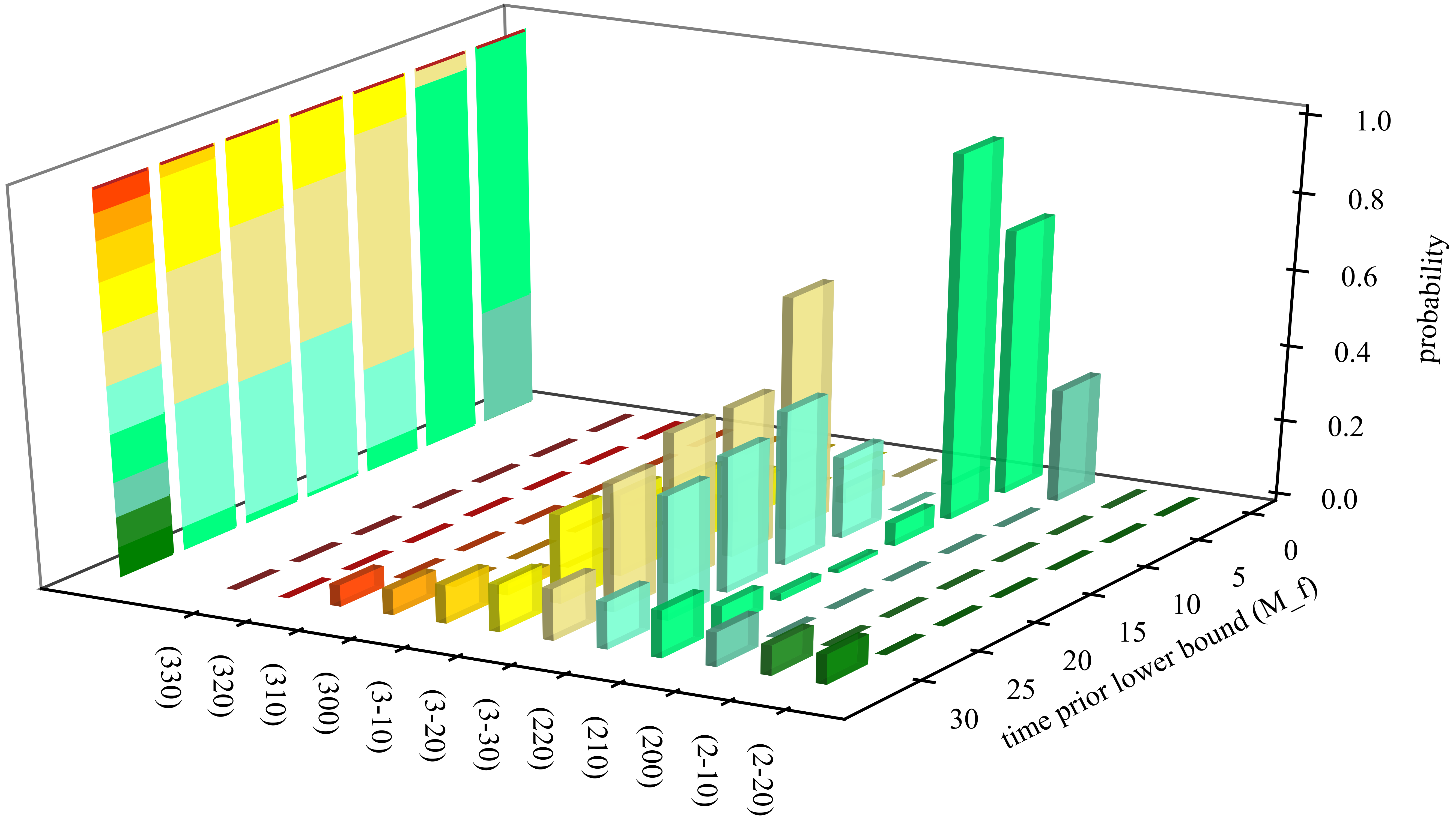
DEPENDENCE ON TIME PRIOR

- What is the effect of the time prior?





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DEPENDENCE ON TIME PRIOR

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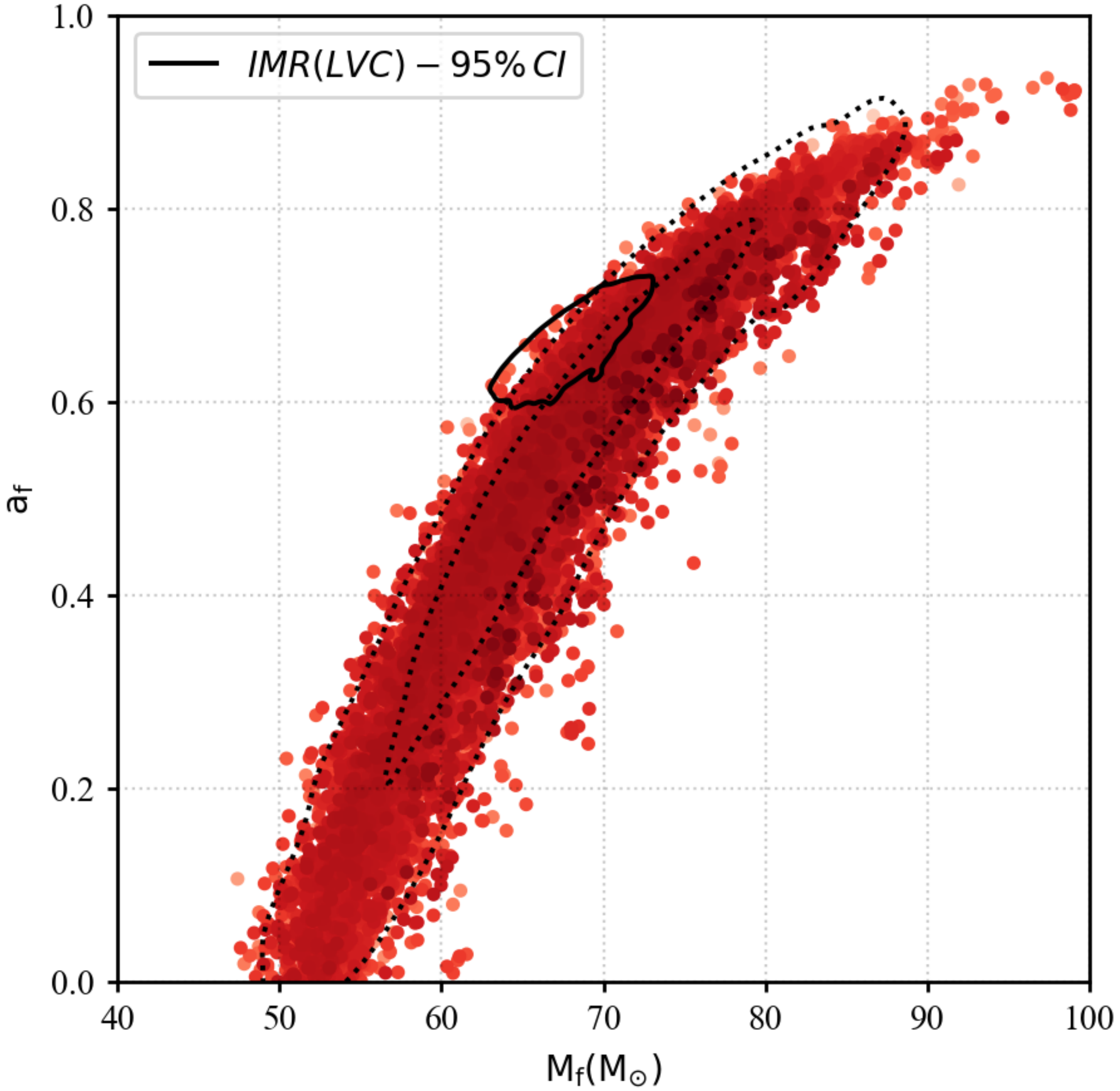
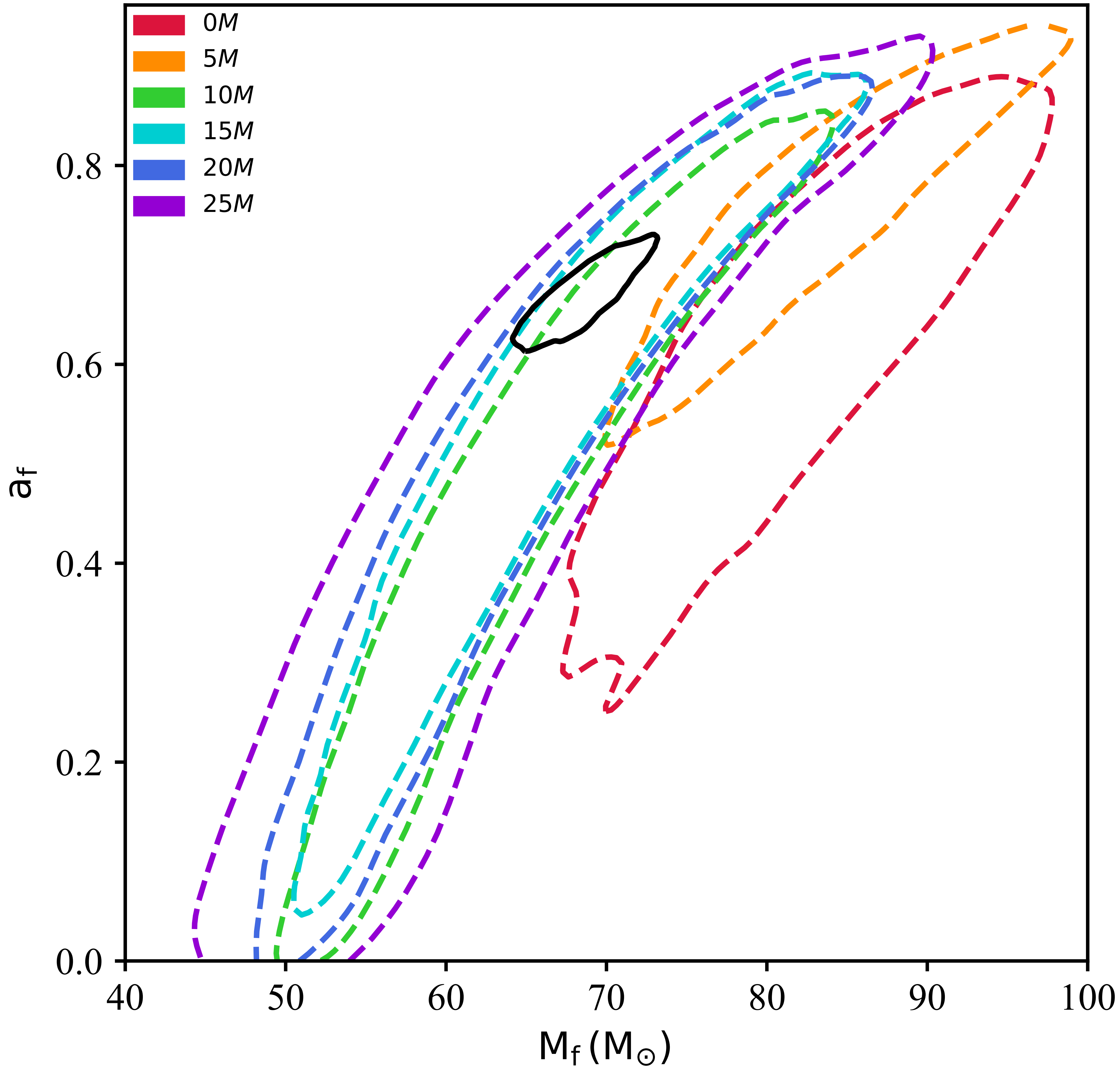
- Remnant mass and spin reconstruction:



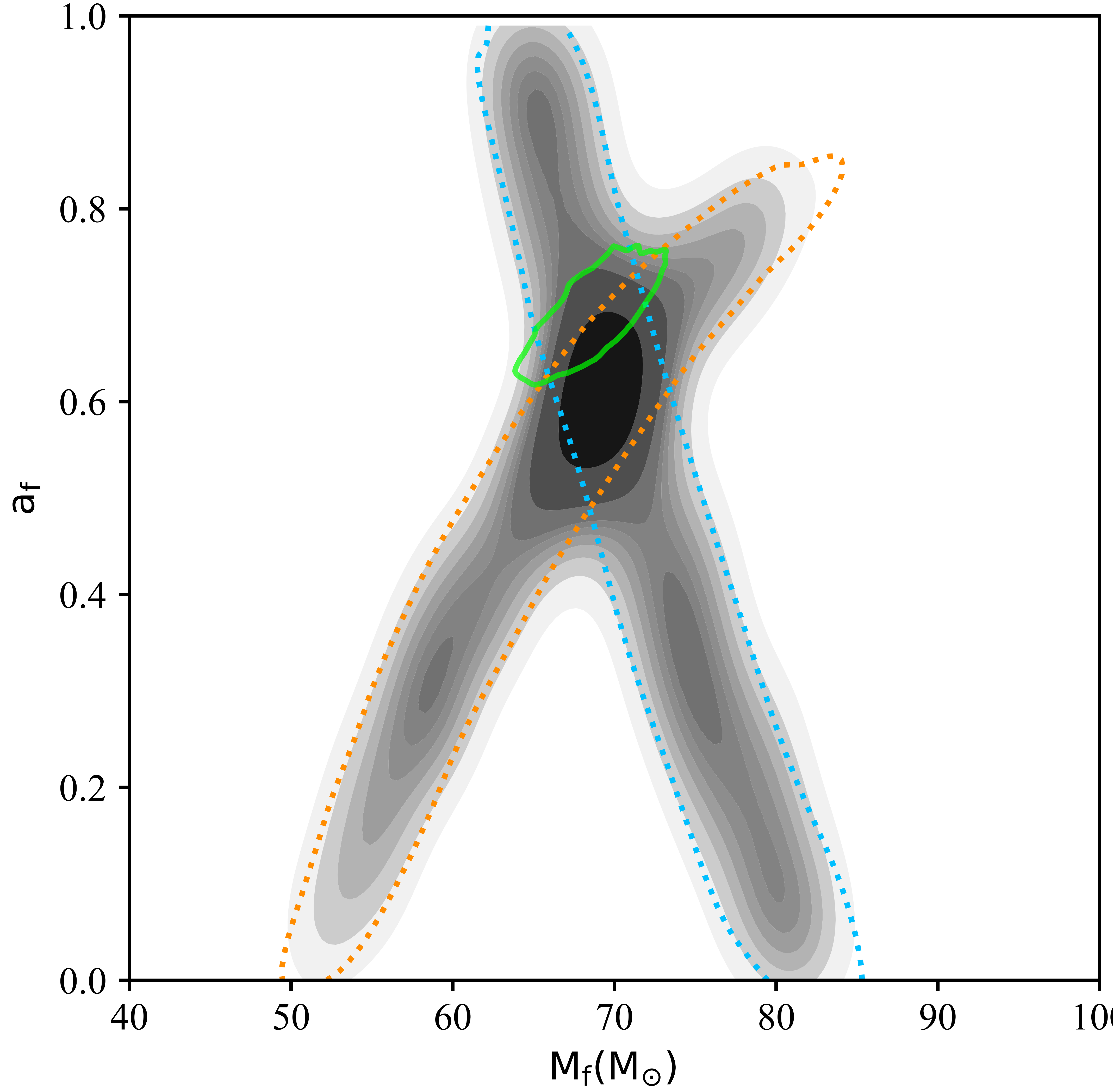


Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)

10M prior

MULTIMODAL KERR ANALYSIS

Model	$\log B_{s,n}$	$M_f/M_\odot$	a_f
IMR (LVC)	-	$68.0^{+3.2}_{-3.0}$	$0.69^{0.05}_{0.04}$
DS - 1 mode	56.3	-	-
DS - 2 modes	55.4	-	-
Kerr - (2,2,0) mode	56.5	$64.6^{+14.3}_{-11.4}$	$0.50^{+0.28}_{-0.40}$
Kerr - (2,1,0) mode	56.6	$61.2^{+8.9}_{-8.5}$	$0.60^{+0.28}_{-0.49}$
Kerr - (2,0,0) mode	56.0	$55.0^{+4.1}_{-4.1}$	$0.69^{+0.27}_{-0.58}$
Kerr - (3,-3,0) mode	57.2	$72.3^{+9.7}_{-8.1}$	$0.46^{+0.47}_{-0.42}$
Kerr - (3,-2,0) mode	57.0	$75.7^{+7.1}_{-5.5}$	$0.49^{+0.44}_{-0.43}$
Kerr - (3,-1,0) mode	57.0	$79.9^{+4.5}_{-3.8}$	$0.47^{+0.46}_{-0.43}$
Kerr - (2,2,0),(3,-3,0) modes	56.7	$69.2^{+12.1}_{-14.2}$	$0.50^{+0.40}_{-0.44}$
Kerr - (2,2,0),(2,1,0) modes	56.2	$62.7^{+15.6}_{-9.9}$	$0.54^{+0.31}_{-0.44}$
Kerr - $\ell = 2$ modes	55.0	$55.1^{+15.5}_{-7.9}$	$0.53^{+0.54}_{-0.46}$
Kerr - $\ell = 3$ modes	54.3	$81.9^{+13.2}_{-10.5}$	$0.31^{+0.54}_{-0.28}$
Kerr - $\ell = 2, 3$ modes	52.0	$56.6^{+27.9}_{-10.1}$	$0.39^{+0.47}_{-0.36}$



- Summary: **not enough SNR** to robustly clearly **claim** more than one mode

Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)

TESTING GENERAL RELATIVITY

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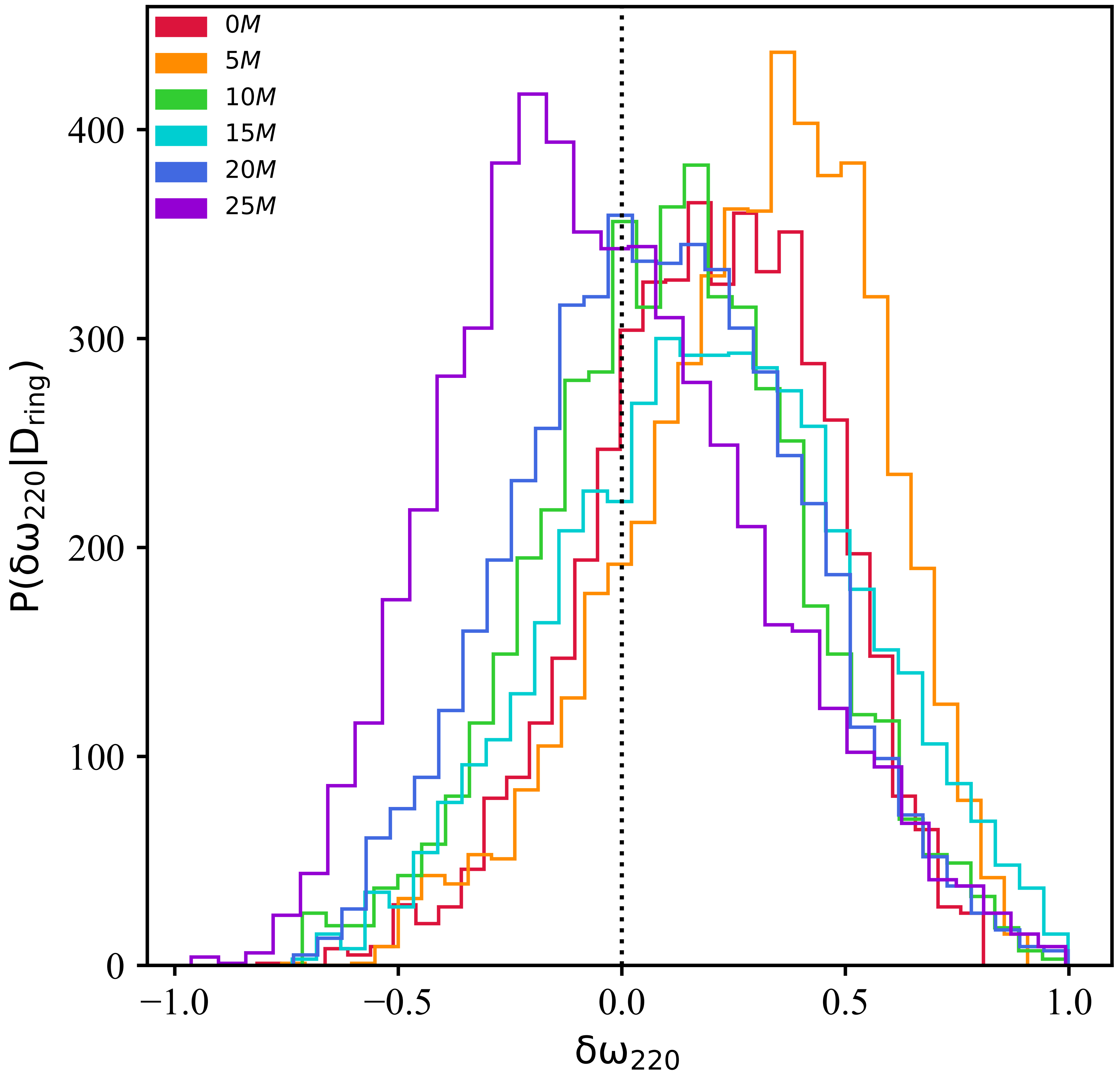
- Parametrized **deviations** from GR:

$$\omega_{lmn}(M_f, a_f) \to (1 + \delta\hat{\omega}_{lmn})\,\omega_{lmn}(M_f, a_f)$$



Gossan, Veitch, Sathyaprakash PRD 85 124056 (2012)

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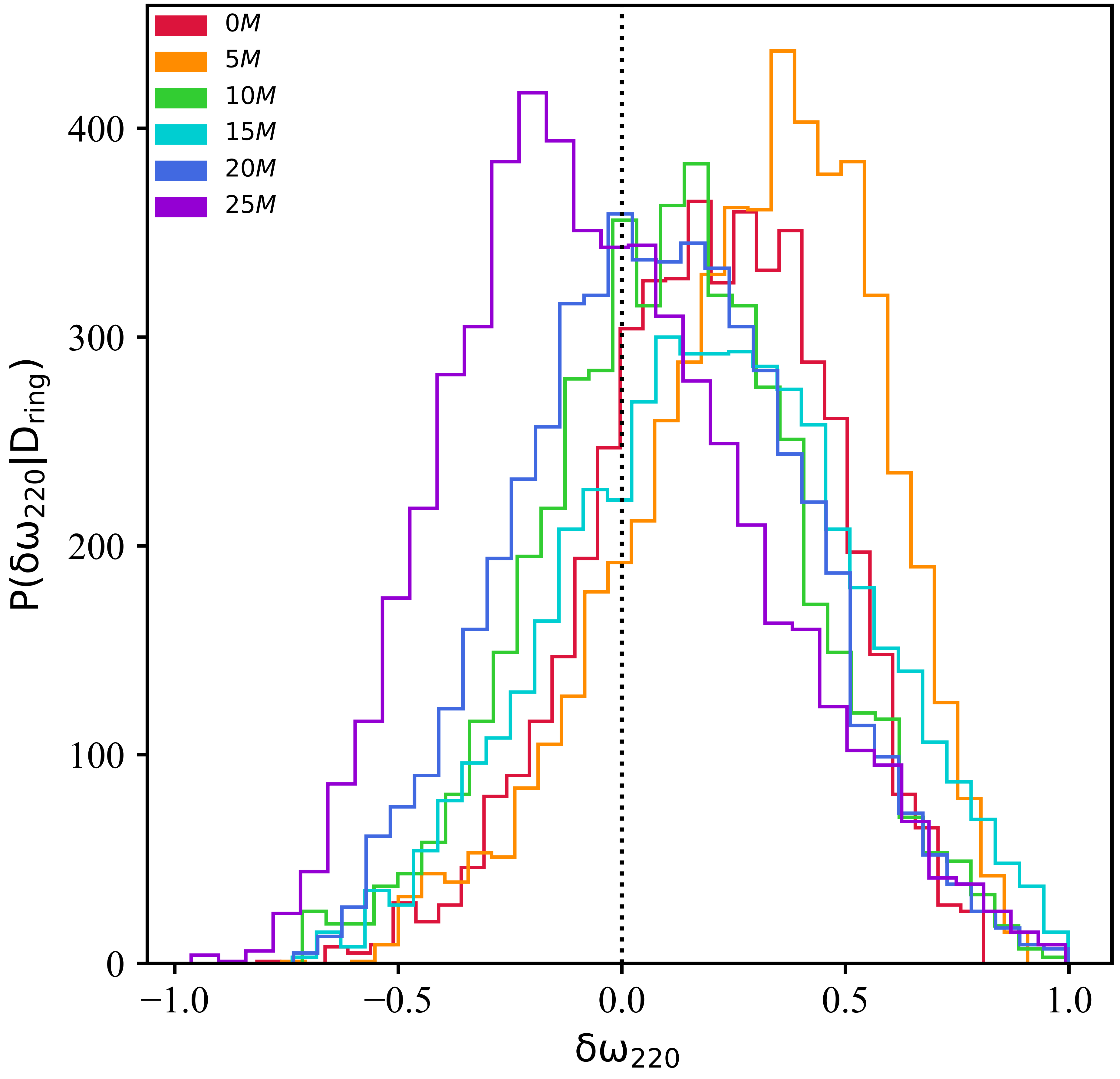
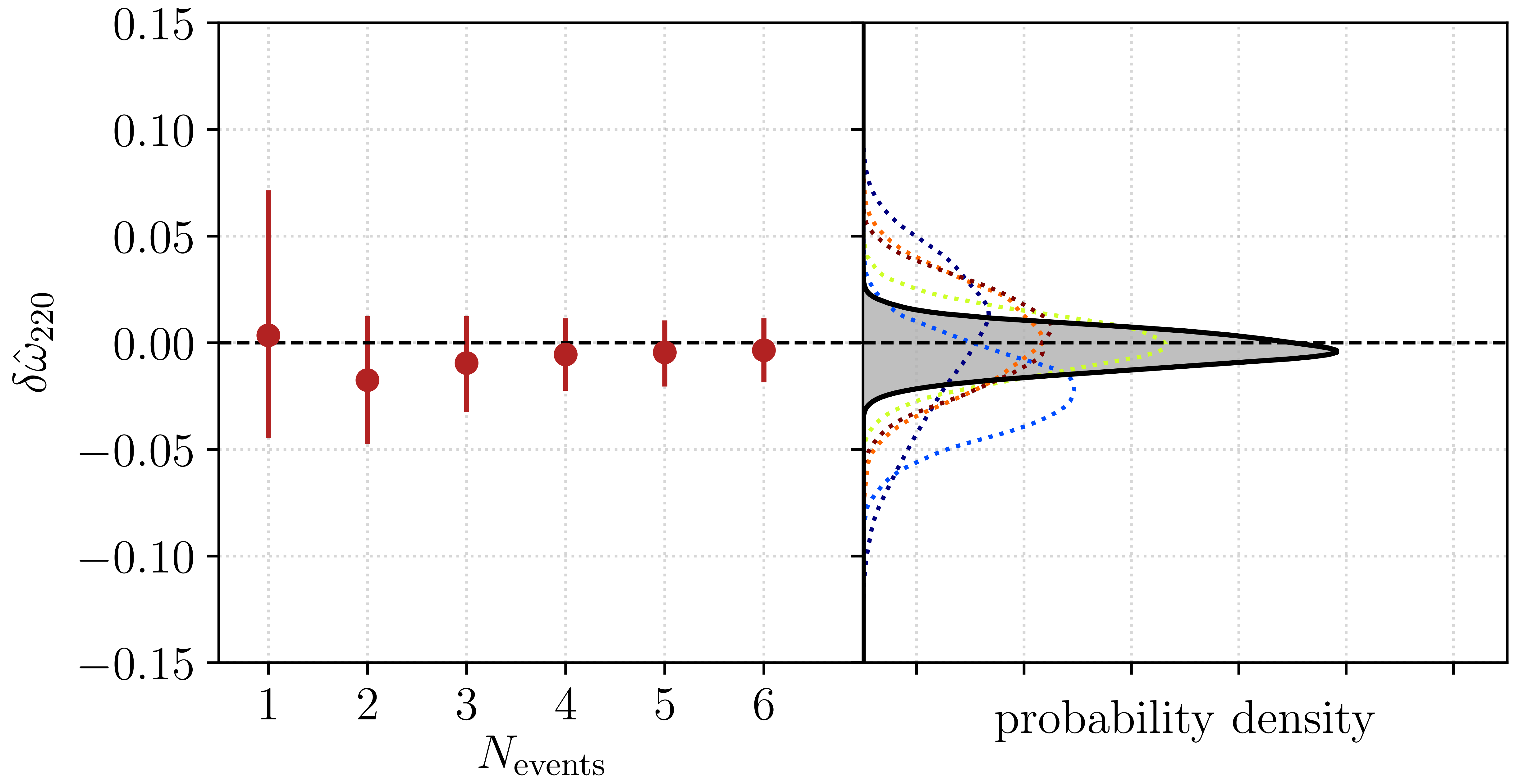


- Future prospects: **1.5%** accuracy with 6 golden events and **LIGO-Virgo** network (design)

- Consistent with what predicted in **Brito, Buonanno, Raymond PRD 98, 084038 (2018)**



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Carullo et al. PRD 98, 104020 (2018)

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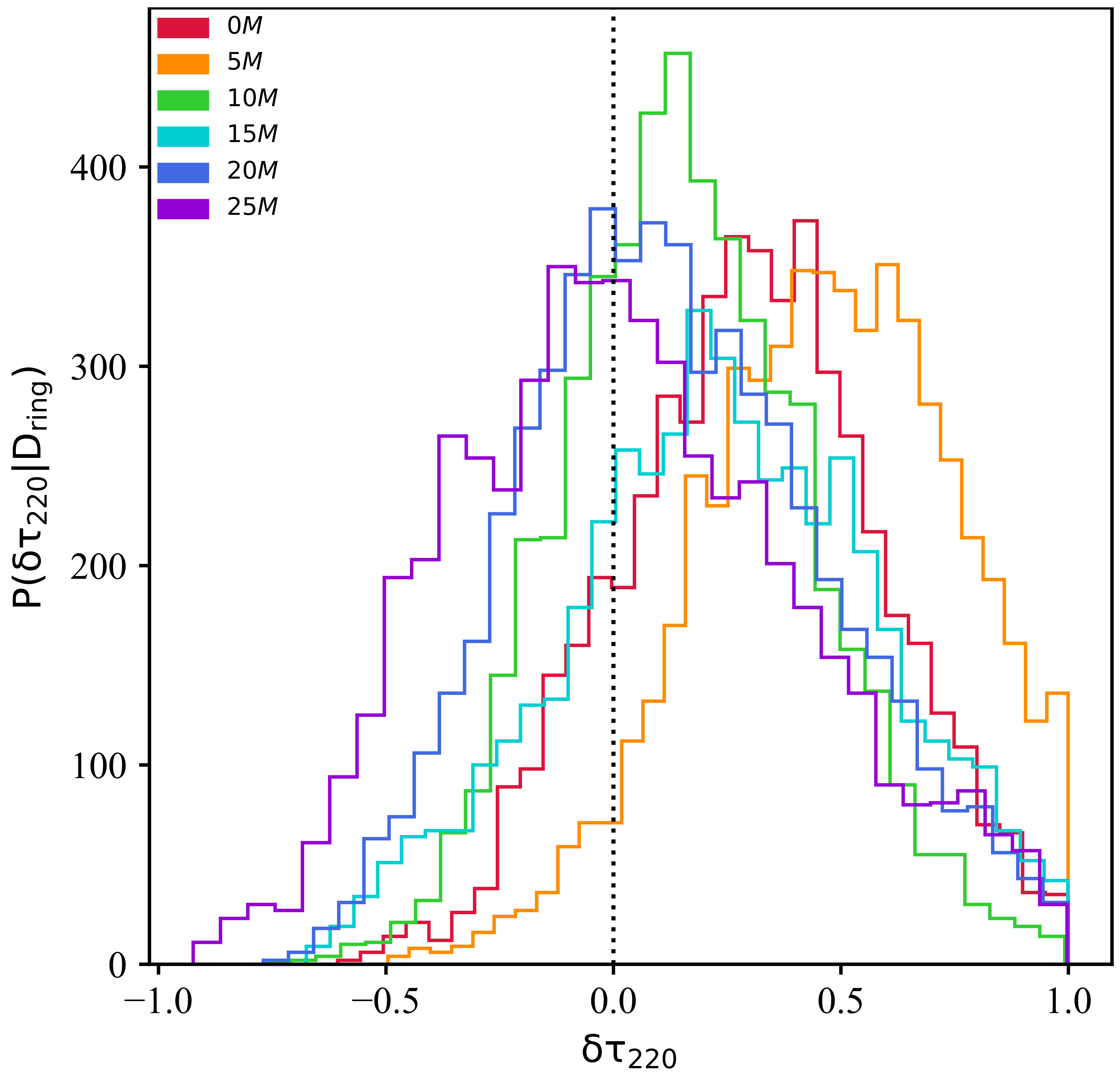

Carullo, Del Pozzo, Veitch, (In preparation)

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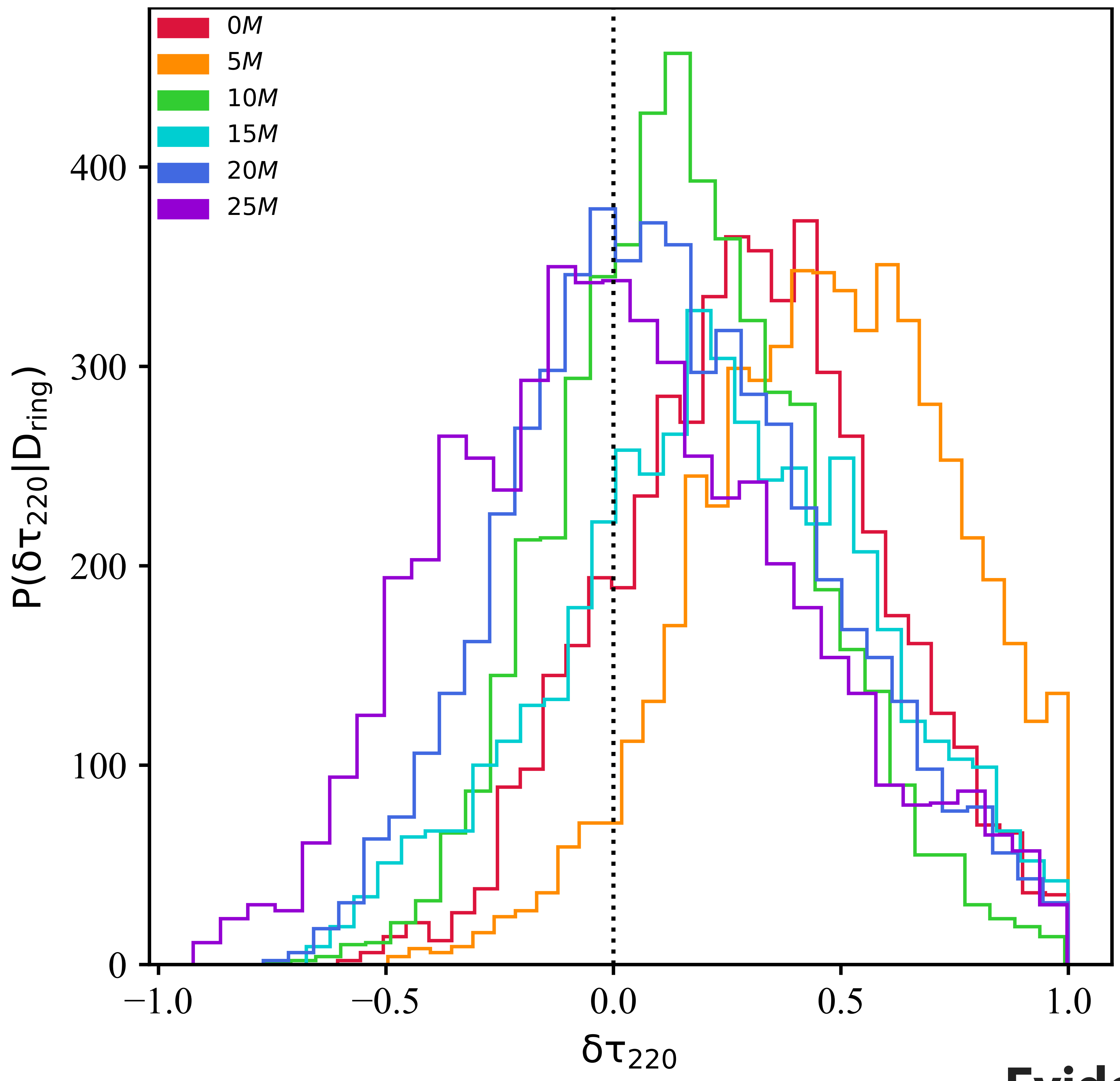
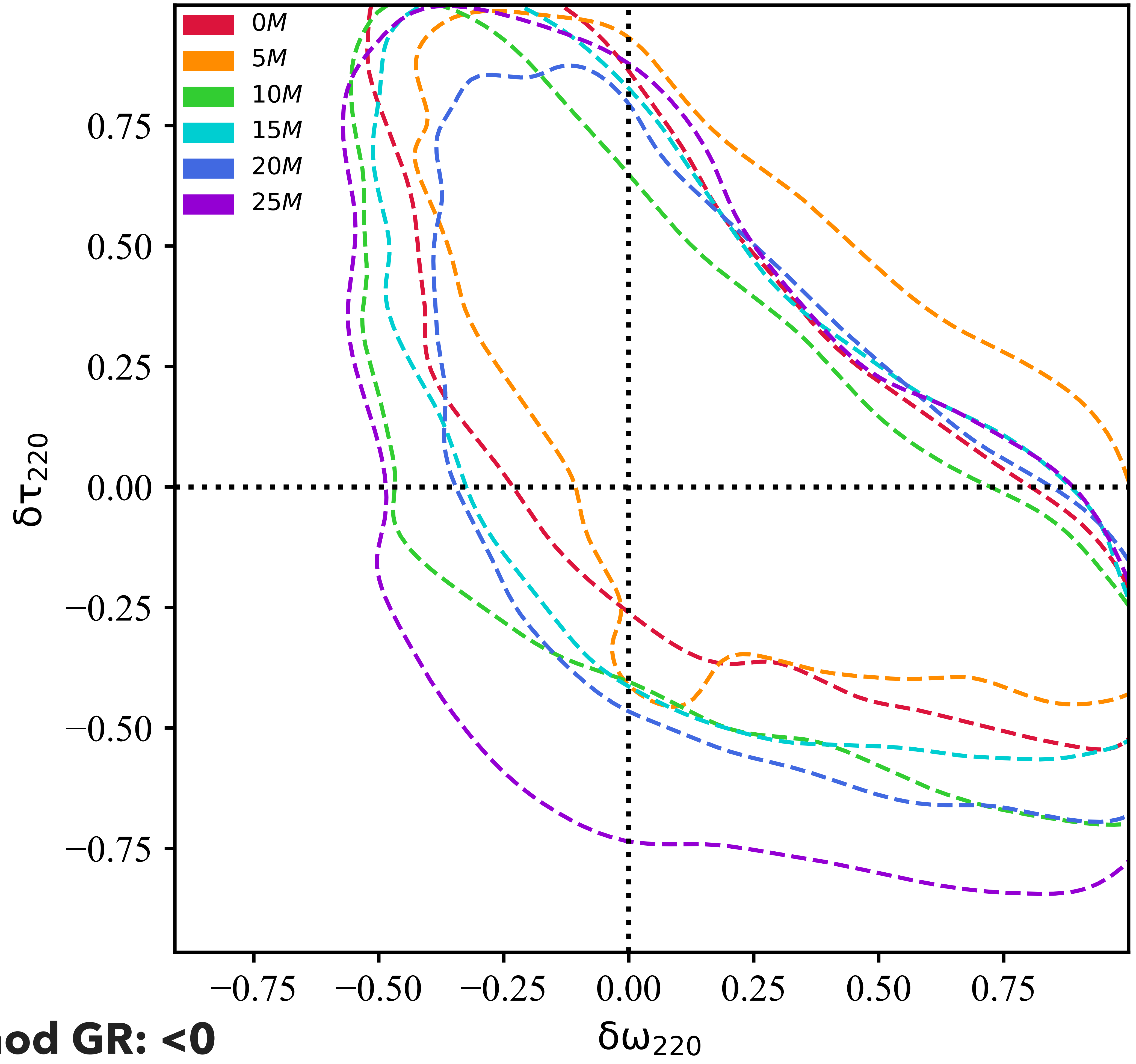


- Sampling the joint distribution:



Evidence for mod GR: <0

Carullo, Del Pozzo, Veitch, (In preparation)

RINGDOWN ANALYSIS ON GWTC-1 CATALOG

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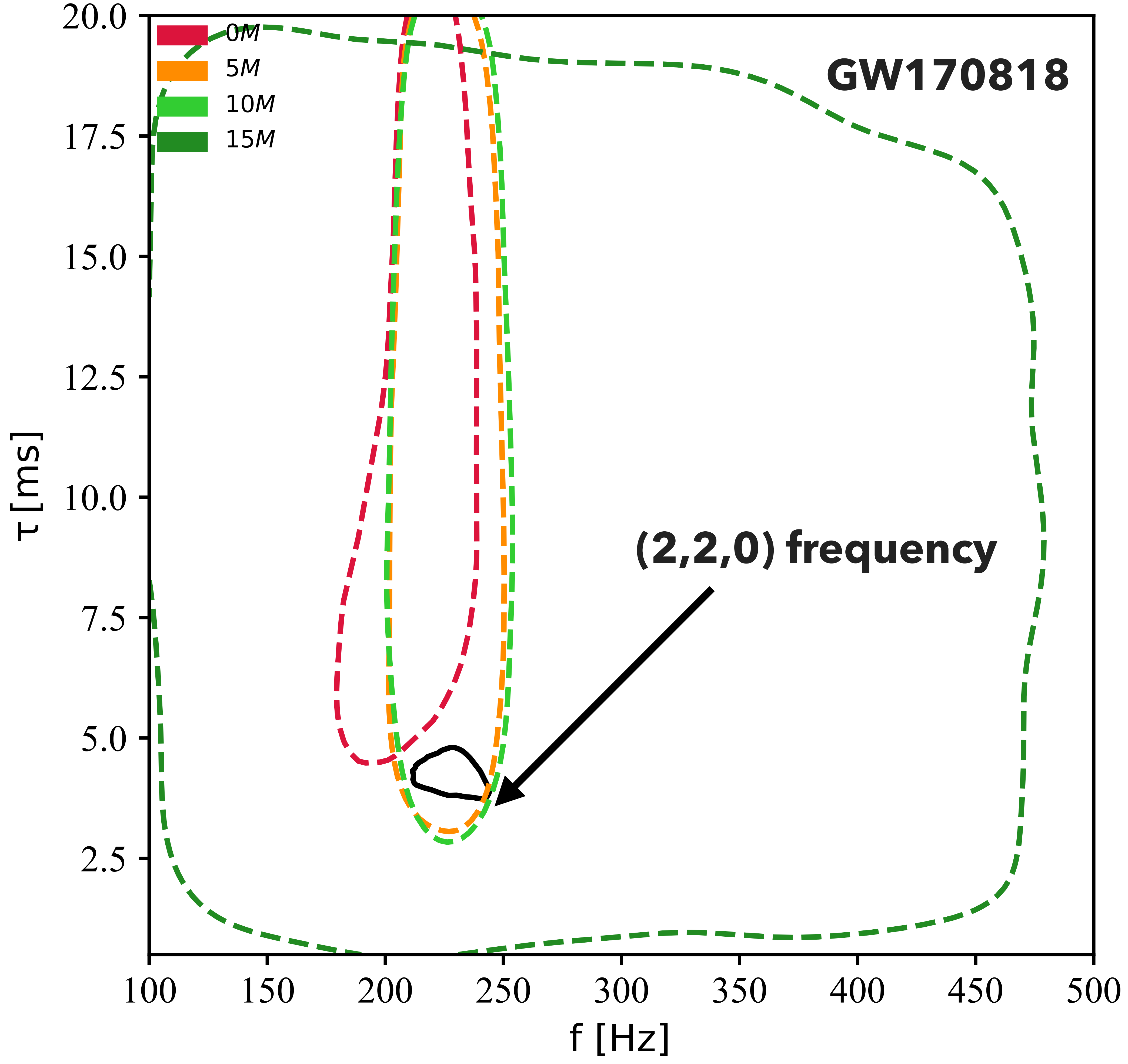
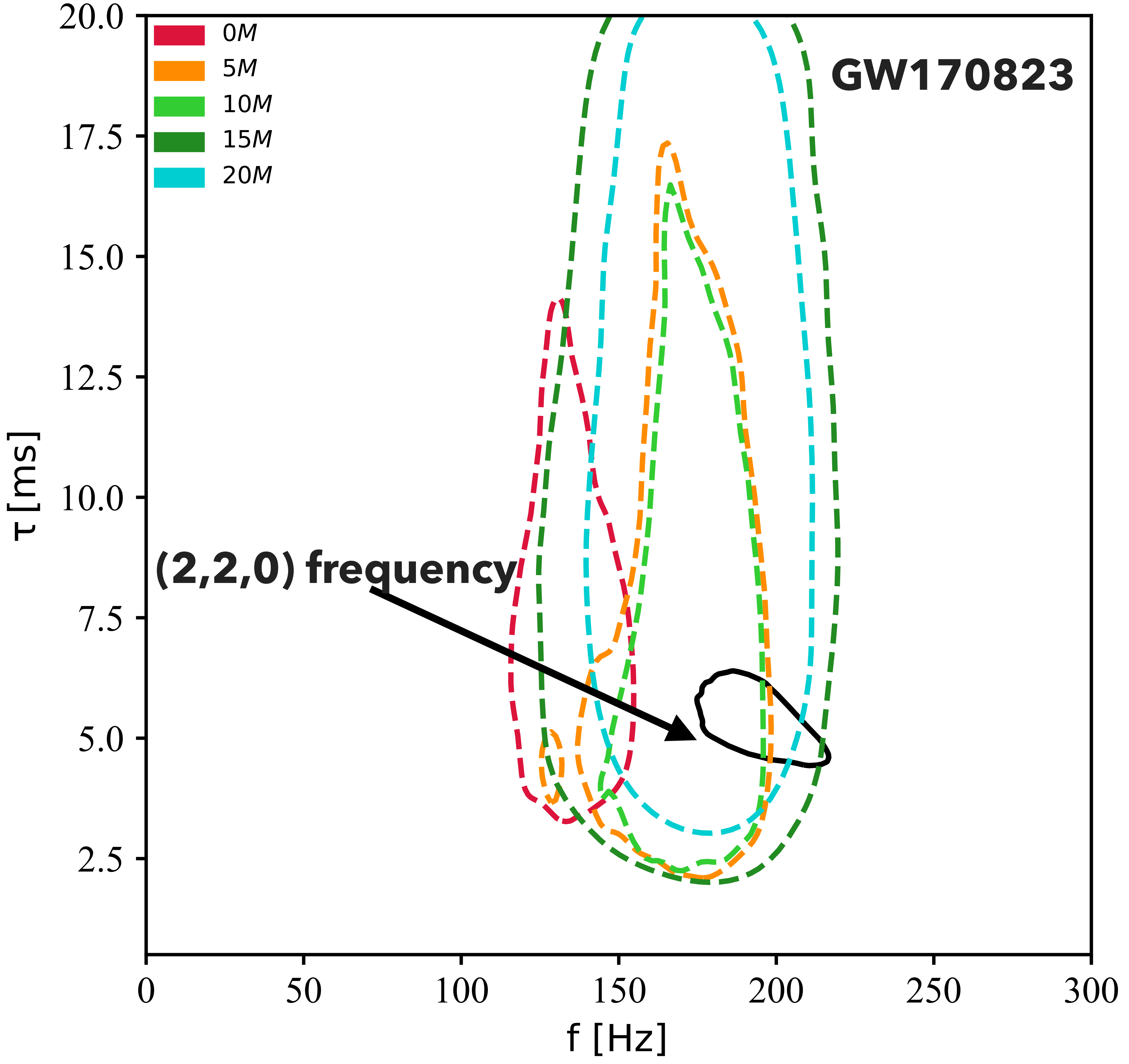
- Iterate on **GWTC-1 catalog** (and automatize in O3):

Black is (2,2,0) frequency





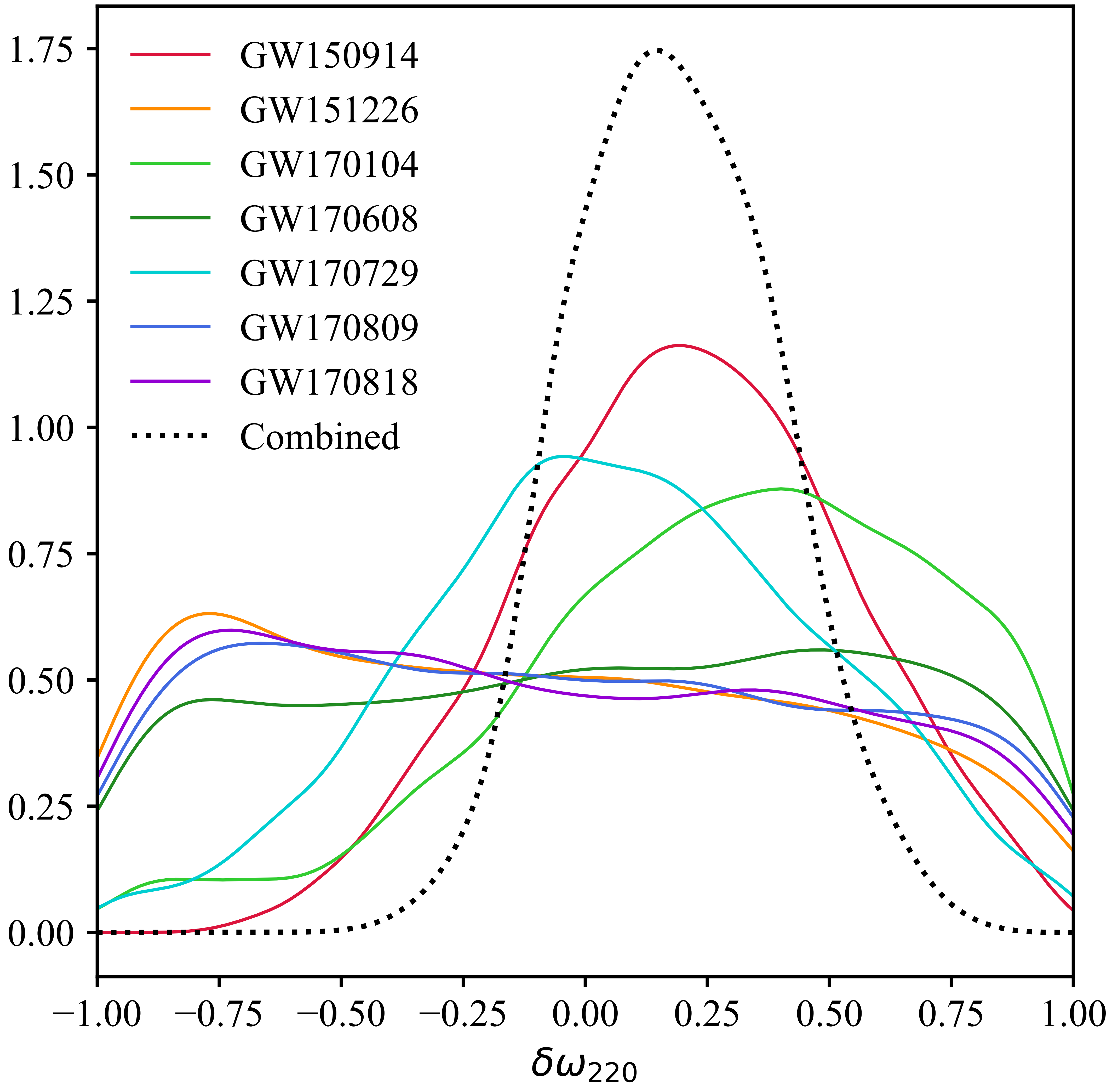
Carullo, Del Pozzo, Veitch, (In preparation)

TESTING GENERAL RELATIVITY

- Parametrized **deviations** from GR:

$$\omega_{lmn}(M_f, a_f) \to (1 + \delta\hat{\omega}_{lmn})\, \omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \to (1 + \delta\hat{\tau}_{lmn})\, \tau_{lmn}(M_f, a_f)$$

- Assume GR as null hypothesis: **combine** constraints



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HIERACHICAL ANALYSIS ON RINGDOWN

- Following the method of [4].

[4] Isi+, Phys. Rev. Lett. 123, 121101 (2019)

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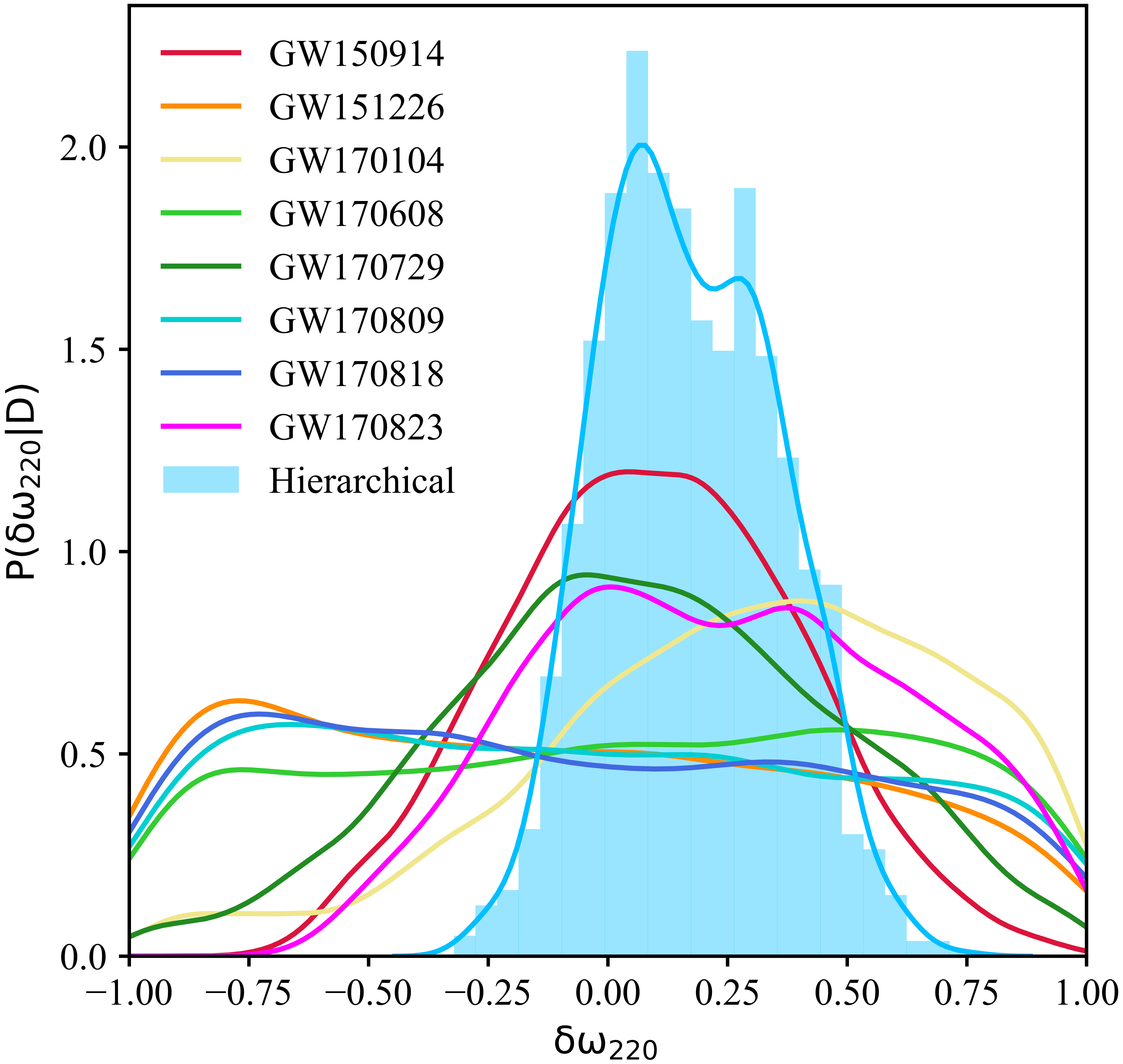
- Put constraints on the **parameters** of such **"parent" distribution**.

[4] Isi+, Phys. Rev. Lett. 123, 121101 (2019)

HIERACHICAL ANALYSIS ON RINGDOWN

- Underlying gaussian distribution on $\delta\omega_{220}$ (fundamental mode case)



CONCLUSIONS

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- **Black hole perturbation theory** is a well-established theoretical framework explored in many **alternative theories** to **GR** (or for alternative compact objects)
- Measurements of **black hole ringdown** are nowadays routinely performed from the LIGO-Virgo collaborations
- **Tests of GR** using ringdown are possible with current detectors, but interesting constraints will need **3G** or **space detectors**

WHY DO WE NEED THIS

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- Test Hawking's **Area Theorem** (Cabero et al., PRD 97, 124069 (2018))
- Test of the Black Hole **Uniqueness Theorems**
- Test **energy** and **angular momentum conservation** during **strong-field** gravitational processes (Ghosh et al., CQG (2017))
- Extract implication on Black Hole **astrophysics** from final **mass** and **spin** measurements
- Test for the presence of **alternative compact objects** (spacetime **signature**), alternative theories or non-vacuum environment (Cardoso, Pani - Living Reviews in Relativity (2019))
- Constrain the **graviton mass** (Chung, Li (2018))
- Test **quantum horizon** effects and classical **BH thermodynamics** (Foit, Kleban, Hod (2019))

See talk from Danny Laghi (tomorrow, 16.45):

"Testing The Area Quantisation Hypothesis From Black Hole Ringdown Signals"

for further applications of this approach.

Credits to: Jani, Ghonge